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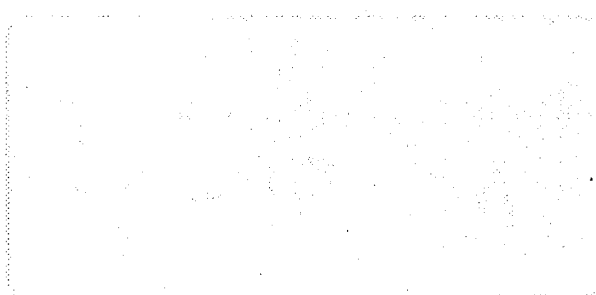
ECG, INC.

Technical, Engineering and Management Services

Survey Plan

Volume I & Volume II

A Window to What Lies Beneath



NASA's Marshall Space Flight Center

Survey Plan

For Characterization of the Subsurface Underlying the National Aeronautics and Space Administration's Marshall Space Flight Center in Huntsville, Alabama

NASA / MSFC Contract Number: NAS 8-40617

Volume I & Volume II

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ACKNOWLEDGMENTS

This Survey Plan for the characterization of the subsurface underlying the Marshall Space Flight Center of the National Aeronautics and Space Administration has been prepared by ECG, Inc., under Contract # NA 8-40617. This Plan contains two integrated parts. Volume 1 is the main Survey Plan and Volume 2 provides appendices for two of the advanced seven technologies considered relevant.

Numerous individuals and organizations have contributed significantly to this effort. They include SRI International, the Houston Advanced Research Center (Geotechnology Research Institute & the Technology Development Laboratory), both as Subcontractors; members of the MSFC Environmental Directorate including the MSFC Program Manager, Mr. Greg Burns; and Radian Geophysics as an associate participant. The principal Investigator and Program Manager, Dr. Yudi P. Gupta, is pleased to recognize, both individually and on behalf of ECG, the valuable contributions of each and every individual which together are too numerous to be mentioned by name here.

List of Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ADEM	Alabama Department of Environmental Management
AGF	Alabama Game & Fish Agency
AM	Amplitude Modulation
AOCs	Areas of Concern
ASCII	American Standard Code for Information Interchange
ATV	All Terrain Vehicles
BMP	Bitmap
CAD	Computer Aided Design
CCD	Charge Coupled Device
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CMP	Common-Midpoint
CoE	Corps of Engineers
CTS	Characterization Test Site
CW	Continuous Wave
CWA	Clean Water Act
DC	Direct Current
DDT	Dichlorodiphenyltrichlorethene
DNAPL	Dense Non-Aqueous Phase Liquid
DoE	U.S. Department of Energy
DTMs	Digital Terrain Models
EM	Electromagnetic
EIS	Environmental Information Systems
ELF	Extremely Low Frequency
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FDEM	Frequency Domain Electromagnetic
FM	Frequency Modulation
FMCW	Frequency Modulated Continuous Wave
GIS	Geographic Information Systems
GPS	Global Positioning System
GPR	Ground-Penetrating Radar
H&SP	Health and Safety Program
HARC	Houston Advanced Research Center
HEM	Helicopter EM
HF	High Frequency
IEEE	Institute of Electrical and Electronic Engineers
IP	Induced polarization
IR	Infrared
IWTF	Industrial Waste Treatment Facility
LAN	Local Area Network
LF	Low Frequency
LLNL	Lawrence Livermore National Laboratory
LNAPL	Light Non-Aqueous Phase Liquid

List of Acronyms (Continued)

MCNP	Monte Carlo Nuclear Program
MF	Medium Frequency
MGAD	MGE Basic Administrator
MGAL	MGE ASCII Loader
MGE	Modular GIS Environment
MGGA	MGE Grid Analyst
MGM	MGE Modeler
MGMAP	MGE Base Mapper
MGNUC	MGE Nucleus
MGTA	MGE Terrain Analyst
MGVA	MGE Voxel Analyst
MSFC	Marshall Space Flight Center
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NDB	Non-Directional Beacon
NURBS	Nonuniform Rational B-Splines
ORNL	Oak Ridge National Laboratory
OS	Operating System
PADAR	Photo-Acoustic Detection and Ranging
PCB	Polychlorinated biphenyls
Pct	Percent
PICT	Picture
PM	Project Manager
QA/QC	Quality Assurance / Quality Control
RDB	Relational Database
RIS	Relational Interface System
RI	Remedial Investigation
RF	Radio Frequency
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RGB	Red Green Blue
SEG-Y	Society of Exploration Geophysicists, format y
SP	Self-polarization
SP	Self Potential
SCS	Soil Conservation Service
SWMUs	Solid Waste Management Units
SAR	Synthetic Aperture Radar
T-M	Transmit - Receive
TARGA	Fle format used in Paint & Video Programs
TCE	Trichloroethylene
TDEM	Time-Domain Electromagnetic
TEM	Transverse Electromagnetic
TIFF	Tagged Image File Format
TIN	Triangulated Irregular Network
TZ	Transition Zone
UHF	Ultra High Frequency

ULF	Ultra Low Frequency
USA MICOM	U.S. Army Missile Command
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USP	Ultra Short Pulse
UV	Ultraviolet
UXO	Unexploded Ordinance
VETEM	Very Early Time Electromagnetics
VGR	Very High Frequency Omni Range
VHF	Very High Frequency
VLF	Very Low Frequency
Z	Atomic Number

Volume I
Survey Plan

Section 1
Introduction and Summary

1.0 Introduction

Concerns about earth's environment continue to prevail. Among these concerns are safe containment and/or remediation of old waste sites and the proper siting for the disposal or storage of future waste. Both problems require geological and hydrogeological understanding of the surface/subsurface supported by geophysical characterization. As the range and scale of these problems expand, increasingly efficient, cost-effective and accurate survey methods are required to characterize the surface and subsurface of sites of concern relative to their geological, hydrogeological, geophysical and contaminant characteristics.

Past activities at the Redstone Arsenal and the National Aeronautics and Space Administration George C. Marshall Space Flight Center (NASA / MSFC) created Hazardous Wastes. Although these wastes were disposed in accordance with the accepted practice then prevailing, it is apparent that many areas have released Hazardous Materials to the subsurface soil, bedrock, and ground water. The U.S. Environmental Protection Agency (EPA) has designated 88 sites as Solid Waste Management Units (SWMUs) and six sites as Areas of Concern (AOCs). As a part of the Superfund Cleanup Program, NASA is conducting a Remedial Investigation of the MSFC in Huntsville, Alabama. The Remedial Investigation represents the first step in the remediation and/or containment of contaminants within the approximately 1,800 acres that make up the MSFC. However, these efforts are complicated by the lack of reliable information about the fate and transport of hazardous contaminants within and without the SWMUs and AOCs. What is required is a delineation of the subsurface features at a fine scale; the features of interest include near-surface (0 to 10s meters) geology, hydrogeology, and the chemical nature, spatial distribution, and migration patterns of any subsurface contaminants.

Traditionally, environmental engineers have estimated the horizontal and vertical extent of subsurface contamination and geological/hydrogeological features by drilling boreholes at selected points or on a regular grid within the Survey Site. The collected samples are subjected to analytical examination, and contaminant concentrations are estimated as a function of depth. The measured concentrations are then plotted on a three-dimensional (D.) map of the Survey Site. Wastesite and Plume boundaries are inferred by linking-up (contouring) the plotted contamination levels. As with any sampling method, the ultimate success of the drilling approach depends on the density of the boreholes. That is, to competently map the Survey Site, boreholes must be drilled on a grid that is dense enough to follow the spatial variations in the geological features, the hydrological environment, and subsurface contaminants. This is not only a very expensive approach but it provides direct data only at the borehole, not in the region away from it. Thus, conventional drilling and construction of groundwater monitoring wells alone is not adequate to define contaminant sources and sinks because of the complex groundwater pathways that Hazardous releases take through the karsted Tuscumbia-Fort Payne aquifers beneath the MSFC. Other more reliable, high productivity and less expensive approaches to subsurface characterization are needed. The hope for achieving the needed characterization lies, with or without suitable modifications, in non-invasive mapping methods that geophysicists have used for geological surveys. Such methods include seismography, electromagnetic sounding, Ground-Penetrating Radar (GPR), gravitometry, magnetometry, magnetotellurics, photoacoustic imaging, and neutron imaging, among other possibilities.

ECG has been involved in the development and application of advanced non-invasive geophysical techniques for environmental characterization of the deep subsurface (10s meters). In September 1995, ECG was commissioned by the NASA MSFC to define and apply an appropriate, non-invasive geophysical sensor (or a suite of sensors) and appropriate survey modalities to obtain a fine scale, geological, hydrogeological and chemical contaminant characterization of the subsurface underlying the NASA MSFC. The work is to be performed in three phases. Phase I involves the development of a Survey Plan with a particular emphasis on the survey of a MSFC selected Characterization Test Site (CTS). Phase II involves the use of technologies, systems and survey strategies, selected in Phase I, to conduct an actual survey at the CTS to validate performance against a set of measures of success, identified below. Phase III entails the survey of the MSFC (about 1,800 acres) using the systems and strategies proven and perfected in Phase II. This Draft Survey Plan is an interim report under Phase I of the program.

1.1 Survey Objectives

The overall goal of this effort is to conduct a geophysical environmental survey of the subsurface underlying the NASA MSFC site. Survey method and strategies shall be cost-effective, non-invasive, and proven to be capable of delineating and mapping subsurface features (geological, hydrogeological, chemical) to a level of detail and resolution consistent with reliable analysis and assessment of contaminant transport and fate. Selected sensors must be effective in probing and imaging a karst underground. Not only must they be operable in generally flat, swampy or wooded environment but they must also provide a capability to map the subsurface underlying the MSFC buildings.

1.2 Survey Success Criteria

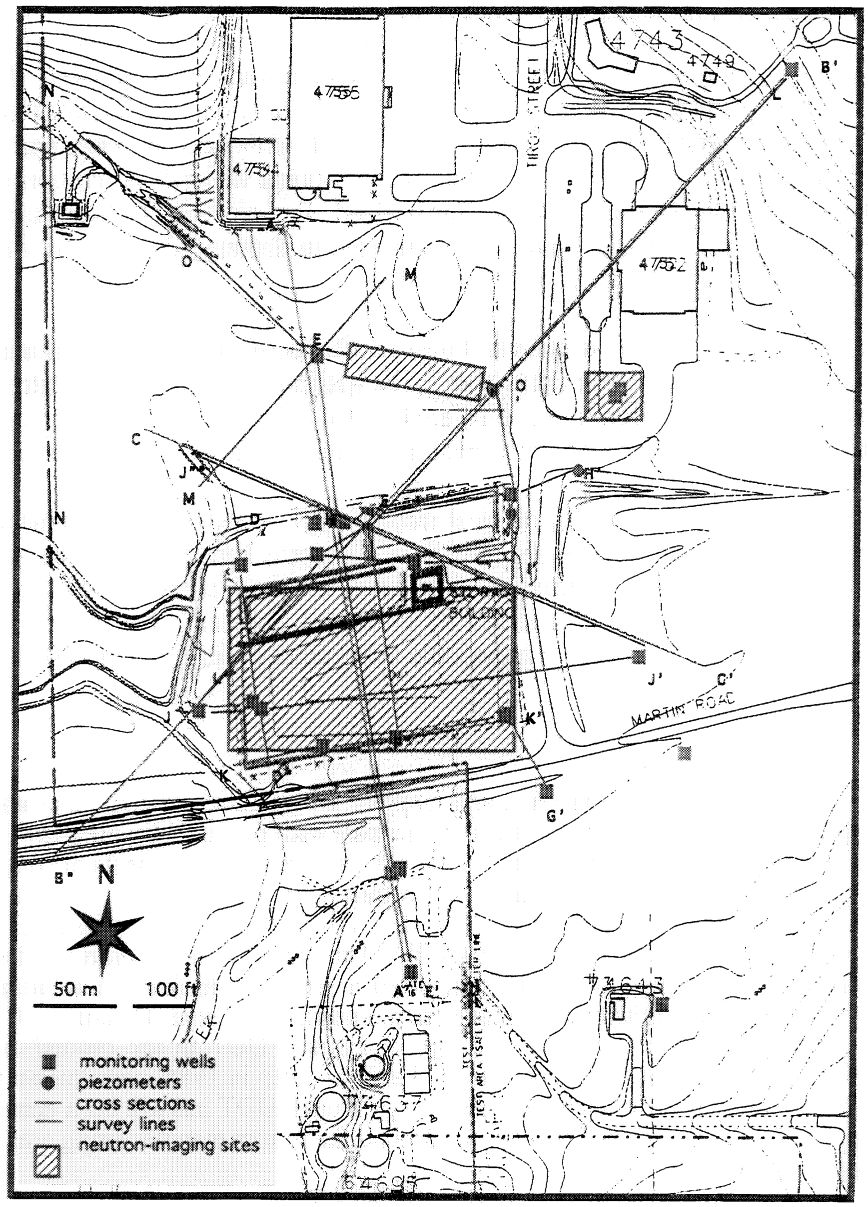
NASA has identified several measures of success for the geophysical approach to the characterization and mapping of the geology, hydrogeology, and contaminant distributions at the MSFC. As measures of success, the selected geophysical sensors must be able, either jointly or severally, to identify, delineate and map: *(a)* occurrences of intact bedrock and zones of high permeability, including voids, caves, sink holes, joints, fractures, and bedding planes; *(b)* sites containing solid waste and regions with contaminant plumes; and *(c)* military objects (*e.g.*, Unexploded Ordinance (UXO)), cultural objects (*e.g.*, buried pipes), and archaeological artifacts. The selected sensor(s) that meet NASA MSFC objectives would be proven at the CTS which has areas within it that have been characterized by conventional well drilling and monitoring methods.

1.3 Baseline Site Characterization

A baseline characterization of the MSFC site was developed with a particular emphasis on the CTS using the available historical data and the information collected from a visit to the CTS. **Exhibit 1.3-1**, a map of the CTS, contains an area of approximately 85 acres. It extends, on the south, past Martin Road to, approximately, the Northern boundary of the Sewage Treatment Plant. Tiros Street transects the CTS from Martin Road North to the parking lot for the Skeet Range, then turns East to intersect Gemini Road. The Northern boundary of the CTS is approximated by the Southern edge of Tiros Street where it turns East. The Western boundary is a line drawn through the point where Indian Creek turns North that intersects the Northern and Southern boundary lines. The Eastern boundary is a line from South to North that approximates the line of the Eastern side of Building 4752. The wetland access road is unpaved and apparently historically provided access to two reservoirs that existed, at least until 1959, on the Western boundary of the CTS.

A Skeet Range lies to the North of the CTS along Tiros Road. MSFC Buildings 4743, 4750, 4752, 4754, 4755 and the Industrial Waste Treatment Facility (IWTF) site lie within the study area. The IWTF is a fenced area that had received wastes from a metal plating facility. The IWTF contains a concrete slab, an abandoned waste settling pond, a storage building and other features in addition to residual contamination from the plating facility. Tiros Street provides access to the IWTF, a road into the wetland, Buildings and Skeet Range.

Characterization Test Site
(approximately 85 acres)



LEGEND
Bold numbers represent Operable Units
Italic numbers represent monitoring well and piezometer locations
DD' is a cross sectional line

SCALE
1 inch = 250 feet

Exhibit 1.3-1: Map of the CTS at the MSFC

The CTS contains 12 designated SWMUs (NASA MSFC, 1993). It also contains 25 monitoring wells and three piezometer wells that were developed as part of the process of meeting the Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) Work Plan (NASA MSFC, 1993). The wells have been used to characterize the geology and hydrogeology of the CTS.

The surface topography is generally of low relief with a slope toward the Southwest. The CTS is located within the 100-year floodplain of the Tennessee River and its tributaries and is transected by Indian Creek. The channel of Indian Creek and its floodplain have produced a wetland that encompasses part of the CTS and has been designated by the Corps of Engineers (CoE) as a jurisdictional wetland. A live spring, which flows into Indian Creek, is located on the Northwest edge of the wetland. Examination of aerial photographs of the CTS taken in 1943, 1959, 1983, and 1994, and during our visit in September, 1995 show that the core of the wetland has been relatively undisturbed for at least 52 years.

The land cover form for the area is deciduous forest on Decatur-Cumberland-Abernathy and Huntington-Talbot-Colbert soils (MSFC Land Cover Form Map). The wetland is classified as palustrine, forested (MSFC Wetlands Map). Non-wetland portions of the CTS are forested upland or maintained in mowed grass. Except for construction sites, the area of the CTS has increased in forest cover over the 52-year period examined.

Monitoring well core data and regional geological records (U.S. Army Missile Command (USA MICOM), 1994) show that Redstone Arsenal, the MSFC, and the CTS overlie karsted limestone over a chert basement. The limestone is structurally complex consisting of numerous fractures, pipes and cavities. The hydrogeology is correspondingly complex. Characterization of local and regional water flows (and corresponding contaminant flow pathways) is difficult or impossible using point-in-time data from the various monitoring wells.

Chemicals:

The efficiency of techniques for the detection and mapping of chemicals at a site depends on the particular chemicals, and at times, on the form they exist in. Chemical data provided by the MSFC for the CTS were analyzed for composition of the top soil, ground water elements, and the chemicals of concern. In conducting this review, we focused, not on the entire variety of chemicals in the site, but on a more compact list of the main chemicals of concern to the MSFC. This list included Trichloroethylene (TCE), Chloroform, Perchloroethylene, Benzene, Xylene, Beryllium, HCl, HF, Aluminum Oxides, Boron Oxides, SO_2, Aluminum, and Cobalt. The MSFC resource document also listed a series of discharge limitations and monitoring requirements for the site. The following elements were specifically listed: Cadmium, Chromium, Copper, Lead, Nickel, Silver, Zinc, and Cyanide. We also considered DDT in the ground and surface waters. Significant amounts of DDT, detected prior to remedial actions taken in 1986, were known to have come from the drainage of a former DDT manufacturing area. Even though DDT has not been detected (less than 0.5 ppb) since then in most wells except in those directly around the former manufacturing area, this chemical was retained in the list.

Most of the soil at the MSFC has a high moisture holding capacity. We characterized the CTS topsoil as Sand - 8 pct.; Silt - 35 pct.; Clay -55 pct.; and Organic Matter - 2 pct.. For purposes of assessing certain chemical detection methods, the overall soil was modeled as containing: 50 pct. SiO_2 - 35 pct.. $Al_4Si_4O_{10}(OH)_8$ - 14 pct.. $CaCO_3$ - 1 pct.. FeO. As for the surface water, the principal mineral constituents for Madison County are Calcium, Magnesium and Bicarbonate. A series of chemicals of concern were identified. These chemicals included all the chemicals specifically listed in the available reports as having been detected in excessive quantities on the MSFC site. The list also contained chemicals specifically used on the CTS as well as some chemicals used across the MSFC site in the open environment. **Exhibit 1.3-2** presents a list of Chemicals of Concern.

Types of Chemical	Chemicals of Concern
Metals	Aluminum & Aluminum oxides - Beryllium - Cadmium - Chromium - Copper - Lead - Nickel - Silver - Zinc.
Organic Solvents	TCE ($CHClCCl_2$) - Chloroform ($CHCl)_3$ - Perchloroethylene ($(CCl_2)_2$) - Benzo(a)pyrene ($C_{20}H_{12}$) - Benzene (C_6H_6) - Xylene ($(CH_3)_2C_6H_4$).
Other chemicals	Boron oxides - Cyanide (CN^-) - DDT ($(ClC_6H_4)_2CH(CCl_3)$) - HCl - HF - Mustard Gas ($(ClCH_2CH_2)_2S$) - Phosphorous - Sulfur Dioxide (SO_2).

Exhibit 1.3-2. Chemicals of Concern at the MSFC CTS

This list is based on partial documentation. Nonetheless, it will serve as a measure of success in assessing the capability of the chemical mapping techniques.

1.4 Technologies for Non-Invasive Imaging of Subsurface

Numerous non-invasive technologies, both existing and emerging, are germane to subsurface geophysical characterization. They include seismic, resistivity (nearly direct current), Electromagnetics (EM), magnetometric, gravitometric, ground penetrating radars, photoacoustic imaging, and neutron imaging, among others. The sensor technologies fall into two classes; passive and active. Many of these have been used for geophysical surveys using both airborne and ground-mobile platforms. An assessment of these technologies is provided in **Sections 3.1 and 3.2** together with examples of their relevance to the MSFC site. In addition, we have collected experimental data on limited sections of the CTS by use of two modalities, the resistivity and ground-based EM. The purpose of these experiments was to obtain some information relative to the electrical properties of the soil and how the various stipulated sensor techniques will work at the MSFC site. Preliminary results of the limited resistivity survey are shown in **Section 4.0.**

Magnetometers and gravitometers are passive devices. They measure, respectively, the local magnetic and gravitational fields. Either may be operated from aircraft or on the ground. Despite their conceptual simplicity, these instruments continue to play an important role in mineral and petroleum exploration.

Resistivity is an active technique and requires implanting of electrodes that carry direct-current to measure electrical resistivity of near-surface environments, including karst regions. Induced Polarization (IP) is a low-frequency technique for detecting highly conducting (metal) objects. Self-polarization (SP), a passive technique, measures the naturally occurring electrical potentials at the earth's surface and is the approximate electrical analog of magnetometry. In the passive version of the magnetotelluric technique, the geophysicist measures the naturally occurring electric and magnetic fields at a sequence of frequencies in the subsonic (or audio) band and then uses inversion software to infer the soil resistivity as a function of depth.

The seismic instruments are active devices, which must be operated on the ground with imbedded sensors. In practice, the geophysicist illuminates the survey zone with vibrational energy, either impulsively or harmonically, producing thereby surface (Rayleigh), compressional (p-waves), or shear waves (s-waves), among other possibilities. The reflected, refracted or backscattered energy is recorded with geophone (or accelerometer) arrays and processed with sophisticated inversion algorithms. Despite the high cost of collecting and processing seismic data, these techniques continue as an essential tool for the exploration geophysicist.

The EM techniques are economical, non-invasive, and highly productive, and thus continue to gain in popularity. Like the gravitometers and magnetometers, EM equipment may be operated from an aircraft or helicopter or on the ground. The EM sensors are active instruments, which are operated either as frequency-domain (harmonic-illumination) or time-domain (pulsed-illumination) devices. The EM devices operate in the ELF / ULF / VLF bands (30-30,000 Hz) and make use of induction fields. The frequency-domain methods sense the lateral variations in apparent resistivity; the time-domain methods develop vertical profiles of actual resistivity. GPRs operate in the HF / VHF / UHF bands (30 MHz - 3 GHz) and make use of radiation fields. The radar methods feature high spatial resolutions and non-contact operation, but may be less effective in highly conductive sites. Newly emerging radar technologies include the Transition Zone (30 KHz - 30 MHz) and Ultra-Short-Pulse (USP) radars; advanced signal processing techniques, some of which have been developed by the oil and gas industry at substantial expense; and Very-Early-Time Electromagnetics (VETEM). With the advanced radars, it appears that one can achieve even higher capabilities for soil penetration, spatial resolutions, and automated target detection and discrimination.

Geophysicists often use optical (Infrared (IR), visible, Ultraviolet (UV)) and radio-frequency (microwave, mm-wave) imagery, gathered passively with satellites or aircraft. Likewise, gamma ray spectrometers, operated from the air or ground, provide indications of uranium deposits, maps of radioactive wastesites, and distributions of radon contamination.

On-site, non-invasive chemical contaminant detection and mapping techniques are very important to subsurface environmental characterization. Existing techniques involve invasive methods such as well drilling, sampling and chemical analyses. Techniques among non-invasive methods enabling in-situ chemical characterization include Optical Sensing, Neutron Imaging, and Photo-Acoustic Detection and Ranging (PADAR), among other possibilities. These latter techniques are somewhat in the early stages of field applications but are essentially available for use at the CTS.

All geophysical sensors except those that require, for whatever reasons, ground contact for their operation (*e.g.*, Resistivity, Neutron Imaging), can be used with either platform type; airborne (aircraft, helicopter) or ground-based vehicles. For certain geophysical surveys satellites are also used. The satellite platforms, which include civilian, military, and commercial spacecraft launched by both domestic and foreign agencies, produce imagery in the optical (IR, visible, UV) bands that can be purchased, fused, and visualized with data obtained with other geophysical sensors. Geophysicists use the airborne platforms to carry magnetometers, gravitometers, EM sensors, GPRs, and gamma-ray spectrometers, among other possibilities. The terrestrial platforms include ground-mobile (wheeled), portable (backpack), ground-contact (skids, electrodes, vibrators, geophones), and ground-penetrating devices (penetrometers). Typically, the satellite based devices feature high productivities (square kilometers per day), but lower (>10 m) spatial resolution, except at optical wavelengths, where submeter imagery is often available. The terrestrial methods, by contrast, are far slower (acres per day), but feature excellent (down to 10 cm) spatial resolutions in both vertical and lateral directions.

1.5 Survey System Configuration

The whole range of geophysical survey systems were assessed in terms of their availability, technical performance, relevance to the MSFC requirements (including the operational effectiveness in the specific site environment) and cost-effectiveness All required sensors are readily available. With modifications to certain sensors (*e.g.*, use of advanced GPRs and advanced data processing methods), higher resolution and higher penetration into the subsurface are possible. Non-invasive, subsurface geophysical characterization is technically feasible, however, multiple sensor types are required to obtain the range of information needed.

The sensor modalities selected for use in the follow-up phases of this project are **Ground-based** (Resistivity / SP; Magnetometry; Frequency Domain Electromagnetic (FDEM); Time-Domain Electromagnetic (TDEM) / Magnetotellurics; GPR, conventional and advanced; high resolution Seismic; VETEM (if available from DoE); and Neutron Imaging); and **Airborne** (Helicopter EM; Helicopter GPR; Aerial Photography; Satellite Imagery). None of these modalities would be used to survey the entire site. Rather a survey strategy is derived that provides the data and data quality required while minimizing the cost of the survey.

Data processing, packaging and interfaces to the NASA MSFC Geographic Information Systems (GIS) / Environmental Information Systems (EIS) systems are discussed in **Section 3.5.** There appears to be no serious issues which will complicate the data integration with the NASA systems except that the proprietary algorithms developed by certain service contractors with non-government funds, if used by the NASA personnel, will require either a licensing arrangement or the data may have to be processed at the facilities where such algorithms exist, and the results be provided to NASA MSFC in a format that is compatible with the MSFC systems. The anticipated final data products shall include maps, data tapes or diskettes with possibly MapInfo GIS for interface with NASA GIS, and reports unless otherwise advised.

1.6 Deployment Strategies and Logistics

Geophysical surveys are conducted using both airborne and terrestrial platforms. Each of these modes uses one or more sensors for exploring the subsurface. Sensor information is integrated with a data acquisition / processing system, a geographic information system, and a position reference system. The airborne surveys are used for large sites (100s of acres and above) and for gaining an overview of the Survey Site; the feature resolution depends on several factors associated with a system, its operations, and site variables. The ground-based surveys are normally used for more localized views. They yield, in general, resolutions that for the same sensors are higher than those for the airborne sensors.

Survey companies prefer to use an airborne system with an integrated set of several geophysical instruments, and common electronic, data-acquisition, and navigational packages so different types of surveys can be accomplished at the same time with vey high productivity. The result is a relatively low cost per unit area of survey. In important contrast to the aerial surveys, ground-based surveys are typically conducted on a modality-by-modality basis by geophysicists specializing in their own particular sensors. They process their data sets with their inversion algorithms and use their display software to interpret the recorded data. Traditionally, these professionals handoff their findings to the organization that contracted for their surveys, where an in-house specialist will fuse the data sets on entry into a master GIS. Relative to the aerial surveys, the productivity of ground-based surveys is lower and thus in general, they are more expensive per unit area covered. Obviously, the optimum approach (*i.e.*, an optimum survey system) is some combination of the airborne and ground-based geophysical survey modalities. The optimum survey system is determined by tradeoffs between the mix of modalities, site factors, regulatory requirements, and cost for the given set of survey requirements.

In **Section 4.0**, effects of the CTS and regulatory factors on the survey design and deployment strategy are discussed. While there appear to be no serious requirements for special permits and / or licenses, there will be a need to coordinate various survey activities both with the government agencies (ADEM, FAA) and authorities at the MSFC and the Redstone Arsenal. A Survey Safety Plan, approved by the MSFC, will be required to be in place and the personnel involved in survey performance will have to be trained in appropriate safety procedures.

Site factors such as topography, soil characteristics, climate, vegetation, and SWMUs, etc. influence the survey timelines, sensors and platforms to be used to obtain the required information. For instance, resistivity surveys are most suited when the soil is wet or conductive but GPR surveys are best accomplished in dry conditions. Similarly, those survey modalities that provide a set of data that can be used in conducting a survey with a different modality need to be scheduled first. Based on this analysis, we have established:

* Survey lines for survey of the CTS, **Exhibit 1.6-1**
* Survey timelines, **Exhibit 1.6-2**
* Survey scenario described below in **Section 1.7**

1.7 Costs

Geophysical and environmental surveys vary widely in price; see **Sections 3.1.1 and 3.6.2.** Several factors that influence the cost include the relative number of two-dimensional (2D) and 3D maps produced, the extent of the areas required to be surveyed with the highest resolution and other performance requirements, and weather conditions, etc. For a site the size of the MSFC (about 1,800 acres) the cost of a complete survey providing the information required partly as 2D and partly as 3D maps based on detailed to less detailed investigations can be in the range of $3,000 to $5,000 per acre except in some extenuating circumstances. The survey cost of about $5,000 per acre for the entire MSFC site includes the airborne sensor modalities of EM, magnetometry, gravitometry video imaging, GPR, and a Global Positioning System (GPS). AOCs and "hotspots" are identified by the aerial survey as candidates for detailed 2D and 3D ground-based surveys. They were assumed to occupy 30 percent of the site area. Likewise, it was assumed that the ground-based surveys, although conducted by several contractors, use a common set of survey lines (for data registration and computer visualization). A schematic of the integrated survey is shown in **Exhibit 1.7-1**. Clearly, the non-invasive geophysical surveys of the subsurface are cost-effective. In addition, if credit is available for collateral benefits as discussed in **Section 5.0**, the cost of survey per acre can be reduced by that amount which, of course, is difficult to quantify because it depends on whether or not there is a buyer for that collateral information.

1.8 Conclusions

The currently existing geophysical techniques supplemented with certain advanced techniques in the area of data processing, ground penetrating radars and in-situ mapping of chemical contaminants provide a powerful suite of survey modalities that can be sucessfully used to provide a detailed survey of both the CTS and the entire MSFC site relative to the subsurface geological, hydrogeological and contaminant features. The postulated surveys are essentially non-invasive, capable of meeting the MSFC requirements and objectives, and cost-effective.

The results of the Phase I effort entailing the development of a Plan for Survey of the CTS can be summarized as follows:

* All sensors and equipment required for geophysical survey of the subsurface underlying the MSFC site are readily available. With modifications to certain sensors (*e.g.*, use of advanced GPRs and advanced data processing methods) as discussed in this report, higher resolution and higher penetration into the subsurface are expected.
* The non-invasive, subsurface geophysical characterization is technically and financially feasible. Multiple sensor modalities with an appropriate mix of airborne and ground-based

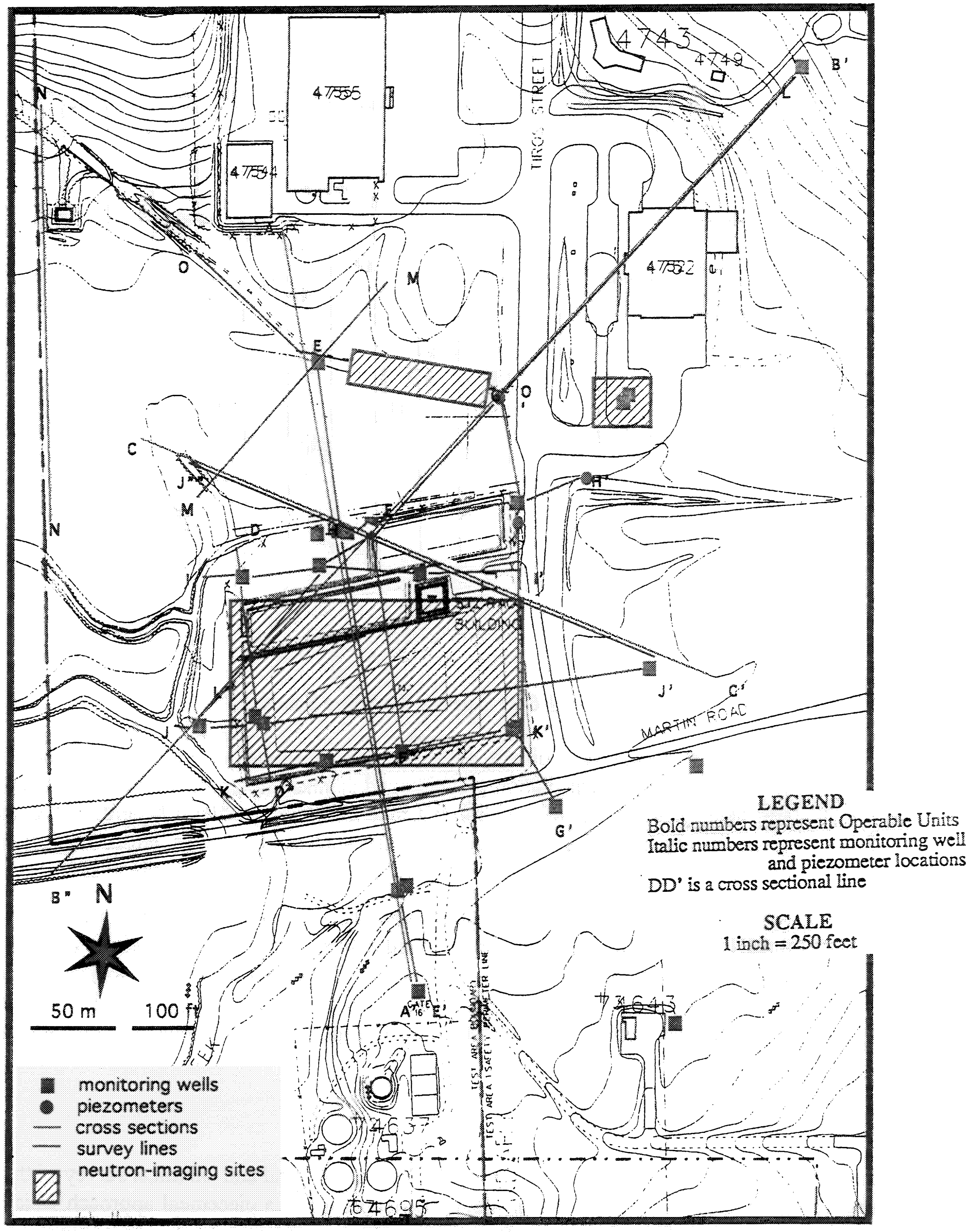


Exhibit 1.6-1: Map showing CTS Survey Lines

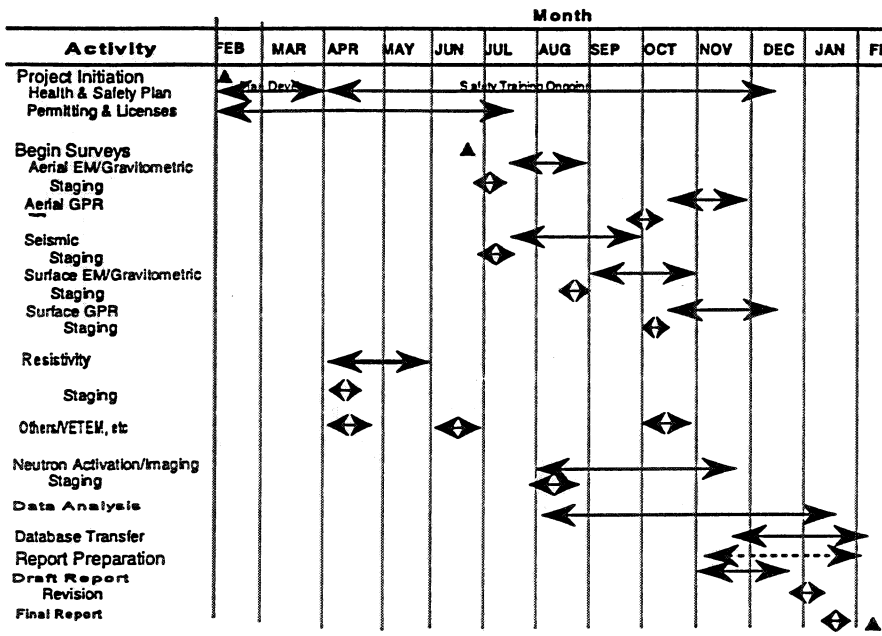


Exhibit 1.6-2: Survey Timeline Schedule

surveys are necessary to obtain, cost-effectively, the range of information needed. The use of such surveys in remediation planning and engineering promises not only to reduce risks, and hence cost, in site remediation but may also yield collateral benefits if the survey of a given site reveals other, long forgotten, assets such as utility lines, archaeological artifacts or buried military objects. The value of these benefits will vary from site to site.

* No serious impediments such as permits and license requirements for conduct of a survey of the CTS or the larger MSFC site are found to be present. Survey timelines and Survey Lines have been formulated for survey of the CTS. They consider the site and regulatory factors and an integrated survey strategy that minimizes the survey cost and provides the quantity and quality of data required to understand the transport and fate of chemical contaminants at the site.

1.9 Recommendations

We recommend an integrated approach to the geological, hydrogeological and chemical survey of the CTS and the site underlying the MSFC. This recommendation is in contrast to a piecemeal approach which provides some data but not a subsurface characterization that would be conducive to an assessment of chemical contaminant pathways and fate. The integrated approach would begin with an analysis of the available historical and observational data which would then be supplemented with overhead imagery, helicopter EM / magnetometry, helicopter-borne GPR and video imaging. Identified AOCs would then be investigated with the productive versions of the appropriate ground-based sensors. Likewise, dentifrice hotspots would be

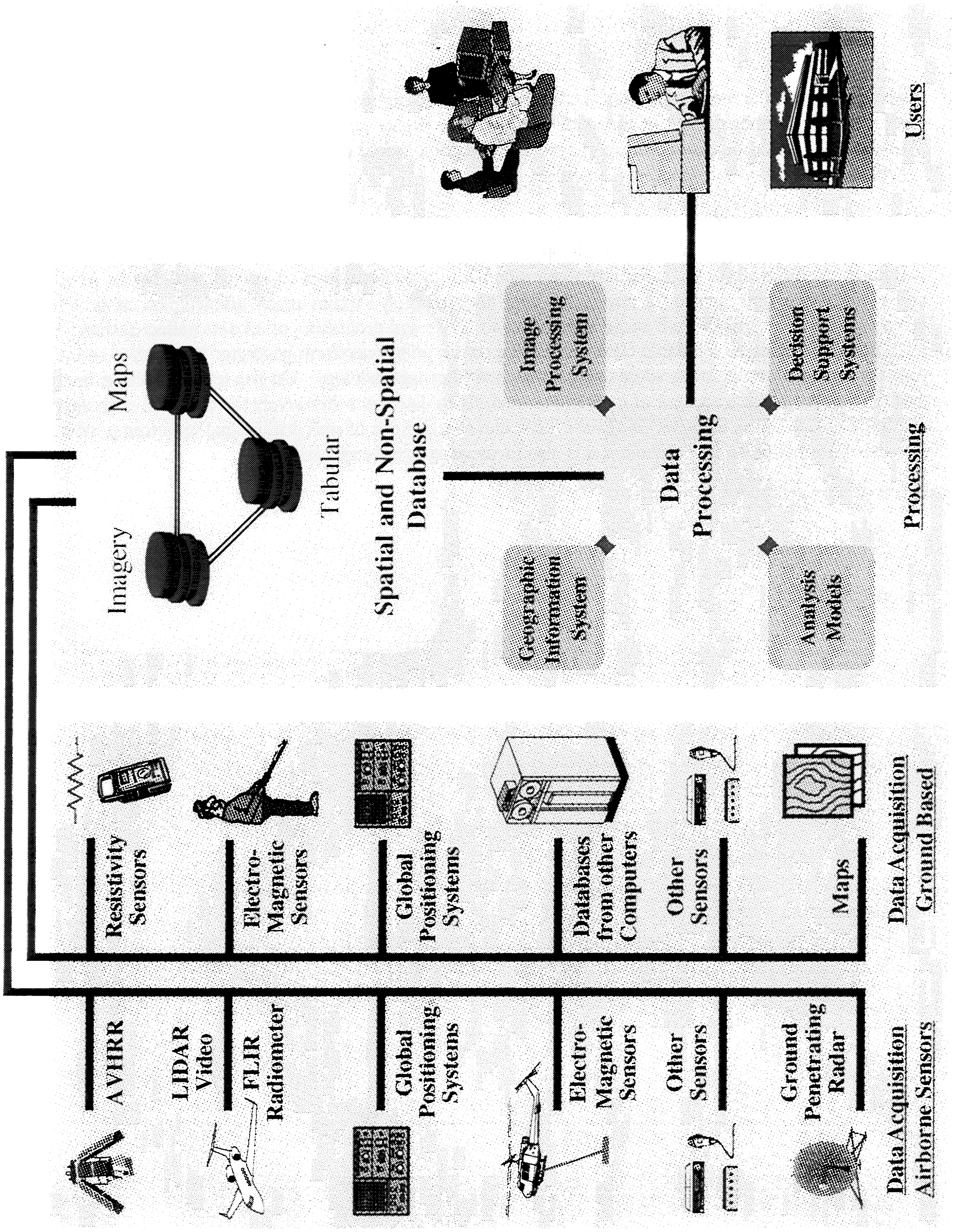


Exhibit 1.7-1: Schematic of an Integrated Survey

investigated with the more competent modalities to provide higher resolution of the subsurface features. In critical areas, 2D imaging will be complemented with the higher resolution 3D mapping. The collected and inverted data would be entered into a master GIS, where it would be fused with other geographic data, and visualized using computer-graphics techniques.

It is recommended that Phase II of the this program, involving a survey of the CTS subsurface, be undertaken. In conducting this survey, advanced GPR approaches and the advanced data processing methods should be validated since they have the capability to provide both higher resolution concurrent with higher penetration and at the same time provide a means for data interpretation without much involvement of professional geophysicists. The included advanced approaches to GPRs and processing of all data collected therewith can be proven by taking an available GPR and adding to it a pulse waveform generator to generate coded USPs for probing of the subsurface while using a matched filter methodology. On-site use of Neutron Imaging at the CTS will be valuable because of its unique capability to detect non-invasively the chemical elements within a volume of 2 to 3m in diameter as against the standard technique of well drilling and monitoring, which only provides information at the borehole and is also invasive and very expensive.

Section 2
Site Description And Characteristics

2.0 General Site Features

NASA is conducting a Remedial Investigation (RI) of the MSFC site in Huntsville, Alabama, as a part of the Superfund cleanup program. The principal objective of this RI is to locate, identify, and map subsurface (surface to about 30 m) contaminants at the MSFC site which is considered to be an essential step in planning and remediation of the site. To achieve this objective successfully and effectively, it is important not only to delineate subsurface geological and hydrogeological features of the site at a sufficiently fine scale but also to determine subsurface contaminants, and their spatial distribution and transport patterns.

A karsted limestone aquifer sits below the MSFC and the adjacent Redstone Arsenal. The spatial structure (vertical and horizontal) of this aquifer is highly complex and rapidly varying. Geologic investigations and borehole sampling indicate a vast array of sinks, artesian wells, natural caves, and underground streams, as well as the more traditional geologic features such as fractures, joints, and bedding planes. The topsoil is Alabama Regolith, a mixture typically consisting of 60 pct. Clay, 35 pct. Silt, 10 pct. Sand, and 5 pct. Organic Matter, kept moist by some 140 cm of annual rainfall. The karsted structures feature rapid (meter-sized) variations in spatial structure. Unless drilled on an extremely dense (one-meter) grid, the traditional drilling and sampling technique cannot meet the basic objectives of the Remedial Investigation. Owing to the cost and impracticality of such drilling, other geophysical methods, preferably non-invasive, are needed for characterization and mapping of the MSFC site. Generally, non-invasive subsurface mapping techniques with potential relevance to the MSFC requirements are sensitive, to varying degrees, to site and climatic conditions. Thus, the relevant site characteristics, both natural and man-imposed, must be understood and defined.

The MSFC is located on 1841 acres (736.4 ha) of the U.S. Army Redstone Arsenal, adjacent to the City of Huntsville in Madison County, in North-central Alabama (NASA MSFC, 1991). **Exhibit 2.0-1** shows a map of the site which contains the CTS that would be used as a benchmark site to validate the suite of non-invasive sensors and modalities to be used for subsurface geological, hydrogeological and contaminant mapping.

The topography of Redstone Arsenal has been characterized as gently rolling hills with elevations ranging from 556 ft (169.5 m) above Mean Sea Level (MSL) in the South to 675 ft (205.7 m) above MSL on the Sorth boundary (USA MICOM, 1994). The highest point on Redstone Arsenal is Madkin Mountain at 1,239 ft (377.6 m) above MSL, which is not on MSFC (USA MICOM, 1994). The CTS contains a jurisdictional wetland as designated by the U.S. Army CoE. A live spring, which flows into Indian Creek, is located on the NW edge of the wetland. Examination of aerial photographs of the site taken in 1943, 1959, 1983 and 1994, and our visit of the Site in late 1995 show that the core of the wetland has been relatively undisturbed for at least 52 years.

The land cover form for the area is deciduous forest on Decatur-Cumberland-Abernathy and Huntington-Talbot-Colbert soils (MSFC Land Cover Form Map). The wetland is classified as palustrine, forested (MSFC Wetlands Map). Non-wetland portions of the Site are forested upland or maintained in mowed grass. Except for construction sites and other areas used frequently within the Site, the area has increased in forest cover over the 52-year period examined.

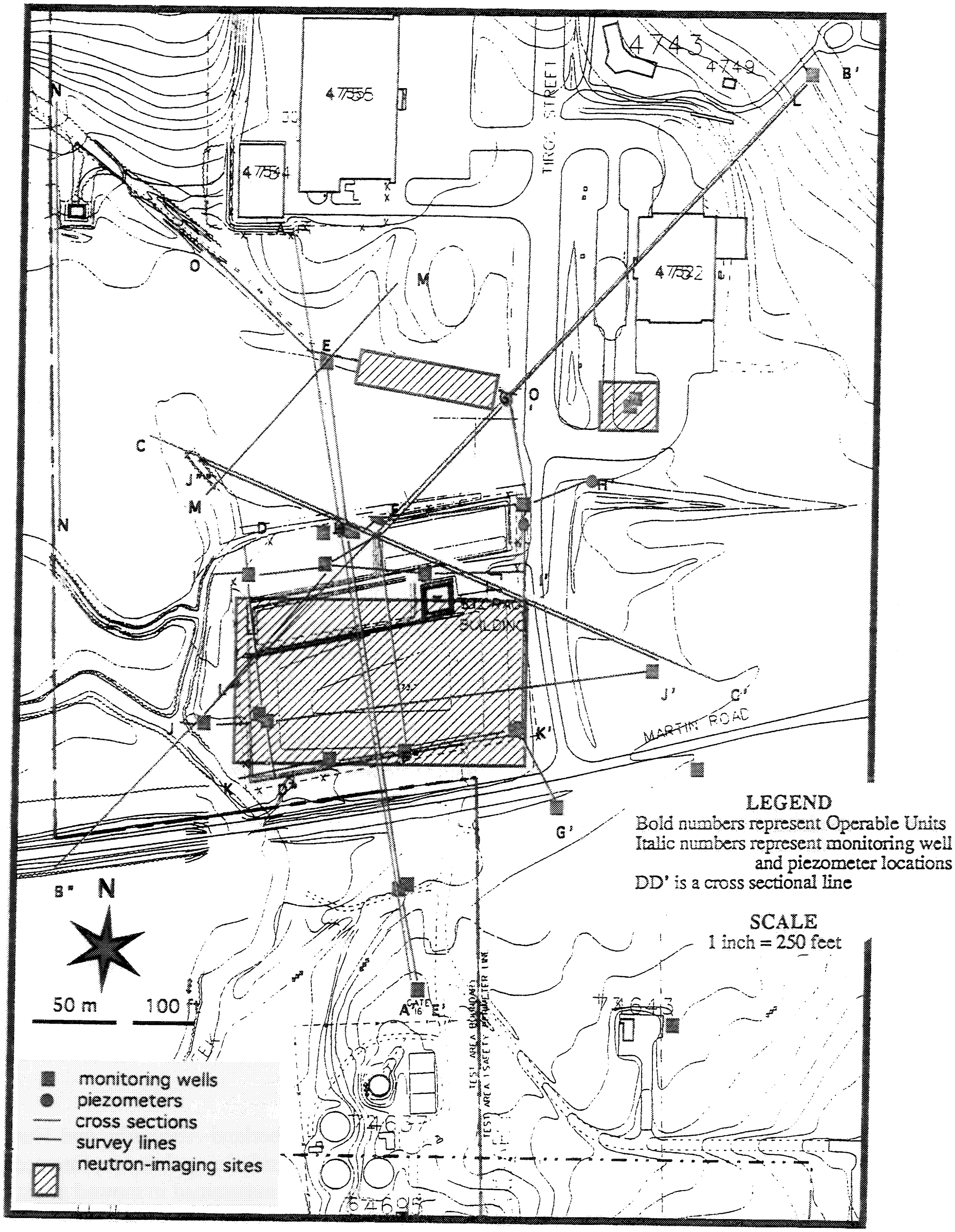


Exhibit 2.0-1: Map of the Site which contains the CTS

2.1 Historical Summary

Redstone Arsenal was purchased in 1941 for use as the site of manufacturing and loading plants for chemical munitions during World War II. In 1951 the Arsenal was assigned the national responsibility for rocket and missile research development and testing (NASA MSFC, 1991, USA MICOM, 1994). In 1960 NASA leased the area for the MSFC from the U.S. Army (NASA MSFC, 1991). Over the past 34 years, the MSFC has been the leader and / or a key participant in many of the most significant space projects and programs undertaken by NASA. These programs include:

- Project Mercury Program
- The Saturn Vehicle Development Program
- Skylab Program
- The Space Shuttle Program
- The Hubble Space Telescope Program
- The Space Station Freedom Program

The MSFC site itself has been, and still is, the principal propulsion development center of NASA. The center is managing the space shuttle's main engines, solid rocket boosters, and external tank. The wastes generated and managed by NASA are organic solvents, rocket fuels, metal finishing and plating wastes, oils, acids, bases, paints, photographic wastes and construction debris. Historical operations that took place on the present day location of the MSFC included the manufacture of mustard gas (dichlorodiethyl sulphide: $uClCH_2CH_2)_2S)$ and white phosphorous incendiary material. A list of the Hazardous Wastes relevant to the MSFC as well as a list of all the Hazardous Substances used at the MSFC are also included in the NASA MSFC Environmental Resources Document (NASA MSFC, 1991).

As a result of the long history of munitions, propellant and missile development and testing at Redstone Arsenal and the MSFC, numerous areas have become sites of significant concern for toxic wastes. A total of 88 SWMUs and six AOCs have been identified at the MSFC by NASA, Redstone Arsenal and the EPA. NASA has developed an RFI Work Plan to address 69 of the SWMUs and 6 AOCs (NASA MSFC, 1993).

The CTS is located on the Central-Eastern boundary of the MSFC and has its own history and characteristics. Twelve SWMUs are on the CTS. Evidence observed on the CTS suggests that portions of the site have been used for dumping quantities of apparently non-toxic solid waste including concrete abutments and portions of steel boiler tanks and pipes.

2.1.1 / 2.1.2 Data Requirements And Sources

Initial data requirements were identified at the start of the project based on potential sensor technologies and modalities that appeared relevant to subsurface mapping consistent with the MSFC requirements. The data categories, identified as required, covered geology, hydrology, surface physiognomy, soil properties including chemistry and electrical properties, maps and photographs, historical usage, structures and buildings, climate, weather, survey data format and integration with the existing databases at the MSFC, and reports of any related environmental and other previous studies. Not only did we receive certain documents from the MSFC but also from its host, Redstone Arsenal.

The CTS characteristics and potential constraints they may impose on subsurface characterization survey of the site were derived from a review of the information contained in the following documents:

1. Final Environmental Assessment for Redstone Arsenal Master Plan Implementation, U.S. Army Missile Command, Redstone Arsenal, Alabama, December, 1994.
2. Draft Environmental Assessment for Test Area 3, U.S. Army Missile Command, Redstone Arsenal, Alabama, Special Report SR-RD-TE-91-46, May, 1991.
3. Natural Resources Management Plan for Redstone Arsenal, U.S. Army Missile Command,Redstone Arsenal, Alabama, June, 1992.
4. Environmental Resources Document, NASA Marshall Space Flight Center, Alabama, January, 1991.
5. RCRA Facility Investigation (RFI) Work Plan, NASA MSFC, Alabama, January, 1993.
6. Miscellaneous maps and data sheets for well logs, wetlands, land cover, water chemistry, and Comprehensive Environmental Response Compensation and Liability Act (CERCLA) chemicals lists, NASA MSFC, Alabama, various dates.
7. Geologic, Hydrologic, and Biologic Investigations in Arrowwood, Bobcat, Matthews, and Shelta Caves, Madison County, Alabama, Geological Survey of Alabama, 1992.
8. The Use of Plant Indicators in Ground Water Surveys, Geologic Mapping, and Mineral Prospecting, Helen L. Cannon, <u>Taxon</u>, May, 1971.
9. Madison County Soil Survey, U.S. Department of Agriculture (USDA), Soil Conservation Service (SCS) (Natural Resource Conservation Service), February, 1958.
10. Aerial photographs of the CTS vicinity from 1943, 1959, 1983 and 1994 with GIS-produced, current, as-built diagrams of roads and structures.

2.1.3 Data Assessment Criteria and Approaches

Criteria and methodologies were established to assess the adequacy and quality of the available site and related data. The criteria included: *(a)* measures of success of the survey techniques, and *(b)* performance of technologies and modalities potentially relevant to meeting the MSFC requirements for planning and cost-effectively deploying remedial actions, as needed. Standard methods were used for evaluating the data available. Methods included careful review of the information available and the development of needed data, where such were not available, with minimal effort in laboratory and field measurements.

The MSFC identified several measures of success for the geophysical survey to characterize and map the geology, hydrogeology, and contaminant distributions underlying the MSFC site. As a primary measure of success, the selected geophysical sensors must be able, either jointly or severally, to identify and delineate occurrences of intact bedrock and zones of high permeability, including voids, caves, sink holes, joints, fractures, and bedding planes. Secondary measure of success includes the ability to identify and map sites containing solid waste *(e.g.*, 55-gallon drums) and regions with contaminant plumes (*e.g.*, TEES). And, as a tertiary measure of success, the selected techniques need to detect and identify military objects (*e.g.*, UXO), cultural objects (*e.g.*, buried pipes), and archaeological artifacts (*e.g.*, Native American pottery).

2.1.4 / 2.1.5 Review of Available Data vs Specific Needs

In general, the available information appeared adequate for developing a baseline description of the CTS, in particular, and its surrounding areas, in general. The baseline description of the CTS will be refined as additional data becomes available. Included in the additional data required are electrical properties of the soil, regulatory requirements including safety and security, operational schedules and constraints that impact on potential survey modalities, survey staging areas, and support facilities. We are currently measuring electrical properties of the soil samples taken from the CTS. Additionally, such data will become available upon our completion of resistivity and EM surveys of a limited area within the CTS on December 16, 1995. This data will be incorporated in the Final Survey Plan report.

2.1.6 Impacts of Unfilled Data Gaps

Actions are underway to rectify the above identified data deficiencies by or before the Final Survey Plan report is prepared. The impact of these deficiencies is, at present, in two areas: *(1)* on performance potential of certain sensor technologies, such as electromagnetic sensors, and *(2)* on certain elements of survey logistics. For example, the MSFC site appears to have a relatively high clay content. Based on prior studies conducted with GPRs, notably that by G.L. Bar (Application of Ground Penetrating Radar Methods in Determining Hydrogeologic Conditions in a Karst Area, West Central Florida, "Water Resources Investigations Report 92", 4141, p.26, 1993) a GPR survey at a frequency of about 80 MHz could be more relevant at the MSFC. The survey at this center frequency may need to be supplemented with data at standard frequencies, 225, 450, and 900 MHz. In view of the areas of impacts identified above, we have been conservative in developing this Draft Survey Plan.

2.2 CST Conditions and Environmental Variables

In this section, we provide a baseline description of the CTS conditions and environmental features as extracted from the available information.

2.2.1 Surface Physiognomy

The CTS is a parcel of about 85 acres contained within the boundaries of the MSFC site, covering some 1841 acres (about 736 ha). The MSFC is located within the boundaries of Redstone Arsenal in Huntsville, Alabama. The topography of Redstone Arsenal is characterized as gently rolling hills with elevations ranging from 556 ft (169.5 m) above MSL in the South to 675 ft (205.7 m) above MSL on the North boundary (USA MICOM 1994).

Structures:

The CTS, located in the central portion of the MSFC, includes Tiros Street and Martin Road West of Rideout Road. Several SWMUs, namely: MSFC-2,19, 20, 87, 44 through 50, and MSFC-A, are on the CTS. MSFC Buildings 4753 and 4754 are located just North of the center of the CTS and Building 4752 is on the Eastern boundary of the CTS. Buildings 4743 and 4750 are located in the Northeast corner of the CTS. There is a public-access Skeet Range located to the North of the CTS. The IWTF site is South of the center of the CTS and is accessed from Tiros Street. The IWTF is a fenced area that had received wastes from a metal plating facility. It contains a concrete slab, an abandoned waste settling pond, a storage building and other features in addition to residual contamination from the plating facility. The CTS contains 12 designated SWMU's (NASA MSFC, 1993). The CTS also contains 25 monitoring wells and three piezometer wells that were developed as part of the process of meeting the RFI Work Plan (NASA MSFC, 1993). The wells have been used to attempt to characterize the geology and hydrogeology of the CTS.

The Western boundary of the CTS is a line drawn through the point where Indian Creek turns North and intersecting the Northern and Southern boundary lines. The Eastern boundary is a line from South to North that approximates the line of the Eastern side of Building 4752. The wetland access road is unpaved and apparently historically provided access to two reservoirs that existed, at least until 1959, on the Western boundary of the CTS. The reservoirs are evident in the 1959 air photo and the previous location of the reservoirs is still evident in the aerial photos from 1983 and 1994.

The CTS contains 12 designated SWMU's (NASA MSFC, 1993), 25 monitoring wells, and three piezometer wells. The wells were developed as part of the process of meeting the RFI Work Plan (NASA MSFC, 1993). The wells have been used to attempt to characterize the geology and hydrogeology of the CTS.

Vegetation:

Vegetation at the CTS is characterized as deciduous forest (MSFC Land Cover Form Map). The dominant trees are pines and mixed hard- and soft-wood deciduous including loblolly and slash pine (*Pinus taeda, P. elliottii*), oaks (*Quercus* spp), sweetgum (*Liquidambar styraciflua*), red maple (*Acer rubrum*), and persimmon (*Diospyros virginiana*) (NASA MSFC, 1991). Understory in the forested areas consists of tree saplings and a variety of shrub and vine species including poison ivy (*Rhus radicans*), sugarberry (*Celtis laevigata*), and Virginia creeper (*Parthenocissus quinquefolia*) (NASA MSFC, 1991). Much of the CTS is maintained as open, mowed grassy areas. The area contains a woodlot and small, isolated groups of trees. Approximately 1-2 acres (0.4-0.8 ha) of the CTS along Indian Creek is a U.S. Army CoE jurisdictional wetland which has been essentially unmodified for in excess of 52 years.

Soils:

The predominant soils of Redstone Arsenal are "lean to fat clays with lenses of silty and / or sandy clay" (NASA MSFC, 1991). The soils of the MSFC are predominantly of the Decatur-Cumberland-Abernathy and Huntington-Lindside-Hamblen soil associations (NASA MSFC, 1991, NASA MSFC Surface Soils Map). Decatur-Cumberland-Abernathy soils are described as generally well drained red, fertile soils that are thick over limestone bedrock. The soils are typically found on nearly level to gently rolling terrain (NASA MSFC, 1991). These soils are found on the upland portions of the MSFC. Huntington-Landsat-Hamblen soils are described as moderate to poorly drained soils on nearly level areas of bottom land along larger creeks and rivers. They are subject to flooding (NASA MSFC, 1991) and are found along Indian Creek and in the wetland. The predominant soil of the CTS is Lindside silty clay loam (Swenson et al., 1958), with small areas of Abernathy silt loam and Cumberland loam in the immediate vicinity.

Surface Water Flow/Flooding:

The MSFC is located within the Indian Creek drainage basin, one of five such major basins within Madison County, Alabama (NASA MSFC, 1991). Indian Creek, a tributary to the Tennessee River, cuts through the CTS. Indian Creek is the source of the wetland area on the CTS. The wetland is characterized, using the U.S. Fish and Wildlife Service (USFWS) characterization method, as palustrine, forested, broad-leaved deciduous, permanently flooded, diked / impounded (NASA MSFC Wetlands Map). However, at the time of the CTS visit, during an extended drought, the wetland was dry. Most of the CTS is within the 100-year flood plain boundary of the Tennessee River (NASA MSFC Wetlands Map, NASA MSFC, 1991). There is a small spring that feeds into the wetland in the Western portion of the CTS. In general, surface drainage of the CTS is to the East and South along Indian Creek.

Access for Effective Surveys:

Access to the CTS on foot, by ground vehicle or airborne systems does not appear to be a serious problem. However, certain factors would dictate as to where, when and what type of survey modalities can be used. MartinRoad and Tiros Street, both paved, two lane streets provide easy access on ground to the CTS. Access to the surface of the CTS is along unpaved dirt tracks or short driveway-like roads. Access to the interior of the wetland is along an unpaved dirt road. There are no lateral accesses into the wetland from the road. Surface access to most of the CTS is good and light to medium trucks can get to most areas. The exception is the wetland interior. Access to the wetland is restricted by road and environmental conditions. The wetland may be often flooded, aside from being moderately to heavily forested. Access will be restricted to foot travel or small All Terrain Vehicles (ATV) with balloon tires. Because the wetland is a U.S. Army CoE jurisdictional wetland and is considered as a sensitive habitat (USA MICOM, 1994) vegetation removal and / or earth moving or drilling activities within it will be restricted.

In addition to the dense forest cover of the wetland, it contains numerous items of debris. Apparently the Site has been used historically as a dumping area for large pieces of concrete and various large metal items such as boilers and pipes. The area also contains large mounds of unidentified, buried debris that can influence accessibility.

Existing buildings on the CTS can influence both the modalities and the strategy for conducting surveys. For example, the site can be easily accessed by air (aircraft, helicopter) but special clearances and permits will be required to survey areas close to the buildings. By the same token, different survey modalities will be required to characterize the subsurface directly under the buildings. The presence of personnel working in the facilities can influence the choice of aerial surveys. For some modalities (*e.g.*, airborne radar), the buildings may have to be evacuated during aerial surveys or the surveys will have to be scheduled when the buildings are unoccupied which will influence timing of the surveys.

2.2.2 Climatic Conditions

The climate of the region that contains Redstone Arsenal and the MSFC is temperate. The summers are long and hot with temperatures occasionally exceeding 100°F (37.7°C); humidity is generally high and thunderstorms are frequent (Swenson et al., 1958, NASA MSFC, 1991). Winters are generally cool, with temperatures occasionally falling below freezing and infrequent snow (Swenson et al., 1958, NASA MSFC, 1991). Forty-three percent of the average annual rainfall tends to occur during the interval December to March (NASA MSFC, 1991). Freezing temperatures are most likely to occur during mid-December but may occur during October and November and into March (NASA MSFC, 1991). Spring (March-May) conditions are most variable and Autumn (September-November) tends to be the driest period of the year (Swenson et al., 1958, NASA MSFC, 1991). In 1989, October had the most rain free days of any month. During the interval of 1960-1989, October had an average precipitation of 3.32 in (8.4 cm), the lowest mean precipitation of any month (NASA MSFC, 1991).

Soil moisture is expected to be lowest during the autumn with October having the lowest soil moisture of any month. Soil moisture will be highest during the months of greatest rainfall, December through June. Except in unusually dry conditions, the wetland should have high soil moisture, generally saturated to flooded, during all months of the year. However, the greatest likelihood of dry soil in the wetland will be during October.

2.2.3 Hydrogeology and Geology

Monitoring well core data and regional geological records (USA MICOM, 1994) show that Redstone Arsenal, the MSFC, and the CTS overlie karsted limestone over a chert basement. The limestone is structurally complex consisting of numerous fractures, pipes and cavities. The hydrogeology is correspondingly complex. Characterization of local and regional water flows (and corresponding contaminant flow pathways) is difficult or impossible using point-in-time data from the various monitoring wells. Traditionally, engineers have estimated the horizontal and vertical extent of subsurface flows and contamination by drilling boreholes at selected points or on a regular grid within a survey site. The collected samples are analyzed for flow rates and contaminant concentrations as a function of depth. The results are then plotted on a 3D map of the survey site. Wastesite and plume boundaries are inferred by linking-up (contouring) the plotted contamination levels. However, with this technique boreholes must be drilled on a grid that is dense enough to follow the spatial variations in the geological features, the hydrological environment, and subsurface contaminants. This can not be accomplished at acceptable costs. Thus, the current available information relative to the subsurface geological, hydrogeological and contaminant plumes can be considered as being representative of the borehole area and its near surroundings. Nonetheless, this information will be utilized as a benchmark of success of the non-invasive survey methods to be deployed.

2.2.4 Chemicals

The efficiency of techniques for the detection and mapping of chemicals at a site depends on the particular chemicals, and at times, on the form they exist in there. It was therefore important to identify the chemicals of concern for the CTS. Chemical data provided by the MSFC for the CTS was analyzed for three categories of information, namely: the top soil composition, ground water elemental compositions, and the main chemicals of concern. The specific documents reviewed to extract this information were: Parts of the 1991 MSFC's Environmental Resource Document; Parts of the 1993 RCRA Facility Investigation (RFI) Work Plan; and Parts of the Natural Resources Management Plan for Redstone Arsenal.

Detailed environmental records and the general history of the site have provided significant leads to chemicals we should expect to find. In conducting this review, we focused, not on the entire variety of chemicals in the site, but on a more compact list of the main chemicals of concern to the MSFC. The first selected chemicals were listed in the RFI Work Plan as "preliminary contaminants of potential concern". This list contains the following chemicals: TCE - Chloroform - Perchloroethylene - Benzene - Xylene - Beryllium. Another series of chemicals added to this list were the substances with health concern that are emitted during rocket testing: HCl, HF, Aluminum Oxides, Boron Oxides, SO_2, Aluminum, and CO. The MSFC resource document also listed a series of discharge limitations and monitoring requirements for the site. The following elements were specifically listed: Cadmium, Chromium, Copper, Lead, Nickel, Silver, Zinc, and Cyanide.

We also considered DDT (dichlorodiphenyltrichloroethane), another chemical in the ground and surface waters. Significant amounts of DDT, detected prior to remedial actions taken in 1986, were known to have come from the drainage of a former DDT manufacturing area. Even though DDT was not detected since then in the majority of groundwater samples (less than 0.5 ppb) except from wells directly around the former manufacturing area, this chemical was retained as one of the chemicals of concerns.

To accurately assess the potential of a contaminant analysis technique it is generally important to model the soil composition as well as the surface and ground water compositions for surveys conducted in wells. For example, for the neutron imaging technique, such information is required, in particular, to compute certain parameters (*e.g.*, the average mean free paths of photons and neutrons in the top soil) that are important to assess the sampled volume and survey geometry.

Most of the soil at the MSFC site is composed primarily of insoluble residue produced by chemical weathering of the underlying Tuscumbia limestone. This type of soil has a high moisture holding capacity. This characteristic coupled with the frequent precipitation can lead to significant water fractions for the upper soil.

The water content of the upper soil is an important parameter for various sensor modalities such as GPR, resistivity mapping, and neutron imaging. Even if we characterize the CTS topsoil as an "improved ground," its general characteristics are expected to be: Sand - 8 pct; Silt - 35 pct; Clay -55 pct; and Organic Matter - 2 pct.

Silt and Sand are mostly composed of Quartz. Probably, the clay also contains some Quartz. The top soils were thus modeled as containing 50 pct. SiO_2. Besides, the clay was modeled as being Kaolite based, containing a significant amount of limestone. Iron oxide was also added into the soil mixture to account for frequent iron nodules. The overall soil is considered to be : 50 pct. SiO_2 - 35 pct. $Al_4Si_4O_{10}(OH)_8$ - 14 pct. $CaCO_3$ - 1 pct. FeO, which characteristics of the soil will be further refined with actual analysis during the next phase of this project. As for the surface water, the principal mineral constituents for Madison County are Calcium, Magnesium and Bicarbonate.

Specific Chemicals of Concern:

From the available data, a series of chemicals of concern were identified. These chemicals included all the chemicals specifically listed in the available reports as having been detected in excessive quantities on the MSFC site. The list also contained chemicals specifically used on the CTS as well as some chemicals used across the MSFC site in the open environment. **Exhibit 2.2.4-1** presents a list of Chemicals of Concern.

Types of Chemical	Chemicals of Concern
Metals	Aluminum & Aluminum oxides - Beryllium - Cadmium - Chromium - Copper - Lead - Nickel - Silver - Zinc
Organic Solvents	TCE ($CHClCCl_2$) - Chloroform ($CHCl_3$) - Perchloroethylene ($(CCl_2)_2$) - Benzo(a)pyrene ($C_{20}H_{12}$) - Benzene (C_6H_6) - Xylene ($(CH_3)_2C_6H_4$).
Other chemicals	Boron oxides - Cyanide (CN^-) - DDT ($(ClC_6H_4)_2CH(CCl_3)$) - HCl - HF - Mustard Gas ($(ClCH_2CH_2)_2S$) - Phosphorous - Sulfur Dioxide (SO_2).

Exhibit 2.2.4-1: **Chemicals of Concern at the MSFC CTS**

This list is not complete and is based on partial documentation and should therefore not be used for purposes other than planning for the next phase of this project. For our purposes, this list provides a wide cross section of chemical types which will serve as a measure of success in assessing the capability of the technique we implement in the field for the detection of chemicals and mapping of chemical plumes in the near-surface. The health impact of several of these chemicals can be found in the RFI Work Plan.

2.2.4.1 Fate of Chemicals of Concern

The chemicals of concern at the MSFC site are numerous and include metals, organic solvents such as TCE and PCE, and inorganic compounds and toxic materials like mustard gas. Some of these materials are relatively more reactive than others in the enviroment of the underlying subsurface. The fate of these chemicals depend on various complex factors that encompass: (i) their reactivity and interactions with the subsurface material including biological mechanisms, and (ii) the various geohydrological transport pathways available in that environment. It is highly complex to *ab initio* define the chemical and biological interactions the various chemicals of concern may undergo both with respect to time and their spatial locations. Nonetheless, spatial movement of these chemicals can be anticipated to occur not just through diffusion mechanisms but also because of subsurface and surface water movements through sinkholes, cracks, fractures, porous soil layers, etc.

Toxic organic solvents like TCE and PCE have limited solubility in water and can exist for a long time in the appropriate subsurface regions as pools which act as continued sources of these materials carried downward and laterally through subsurface waterflows. Unlike the hydrocarbons, solvents like TCE and PCE have a higher electrical conductivity than the natural subsurface materials sourrounding it (Ulrych and Sampaio, 1994, "In Search of Plumes; A GPR Odyssey to Brazil"; Society of Experimental Geophysicists, Abstract, page 569). As shown in Section 3.2.1, this property can be useful in subsurface mapping and tracking of these organic solvents.

Section 3
Technology Adaptation to Mission Suitability

This Section provides the technical and performance basis for: *(1)* the selection of sensor and survey deployment modalities and strategies for mapping sites underlying the MSFC, *(2)* data on selected sensors relevant to the MSFC requirements, *(3)* approach to integration of results with the NASA MSFC Environmental Database Systems, *(4)* survey systems and methodologies to be used at the Characterization Test Site (CTS), *(5)* large scale subsurface geophysical and environmental mapping systems, and *(6)* cost projections associated therewith.

3.0 Potential Sensor Technologies For Subsurface Imaging And Mapping

The NASA MSFC has required that the mapping and characterization of the site underlying the MSFC be achieved with sensors (or suites of sensors) that are technically effective, operationally practical, non-invasive, productive, and cost-effective. For technical effectiveness, the candidate sensors must yield technical information that complies significantly with the measures of success set forth by the MSFC. Specifically, the sensors must be effective in probing and imaging a karst underground. It must not only be operable in generally flat, swampy or wooded environment but it must also provide a potential capability to map subsurface underlying the MSFC buildings.

Numerous sensor technologies are potentially available for the non-invasive mapping of the geology, hydrogeology, and chemical contaminants at the MSFC. The expected performance of these techniques will vary greatly, depending on the surface and underground conditions, as well as the survey goals. Accordingly, we have identified both the commercially available, and emerging but essentially available, geophysical sensors; assessed their expected performance; and selected an integrated suite of sensors that meet the MSFC requirements. In developing these recommendations, we considered the objectives of the survey, the nature of the MSFC environment, the operational aspects of the sensors, availability of hardware and software, and costs associated with full surveys.

Geophysicists investigate and map the geological character of underground regions using probes other than borehole sampling. Until recently, the geophysical community focused its attention on the challenges presented in petroleum, mineral, and water exploration. These applications motivated the design and construction of geophysical tools that penetrate to depths of 100s or 1,000s of meters or more and / or covered survey areas 10s to 100s of kilometers in diameter. In recent years, geophysicists have turned their attention to near-surface (0-100 m) investigations, which have important applications in both environmental and geotechnical problems. Near-surface geophysics differs from traditional geophysics in that the ground penetration depth is less critical and spatial resolution more critical than in petroleum and mineral exploration.

3.1 Sensors And Platforms

Classes of Sensors:

The geophysical community uses a wide variety of sensors to investigate underground environments. Magnetometers and gravitometers are passive devices, which measure the local magnetic and gravitational fields, respectively. Either may be operated from aircraft or on the ground. Despite their conceptual simplicity, these instruments continue to play an important role in mineral and petroleum exploration. Resistivity is an active technique that uses direct-current probes to measure electrical resistivity of near-surface environments, including karst regions. IP is a low-frequency technique for detecting highly conducting (metal) objects. Self-polarization (SP), a passive technique, measures the naturally occurring electrical potentials at the Earth's surface and is the approximate electrical analog of magnetometry. In the passive version of the magnetotelluric technique, the geophysicist measures the naturally occurring electric and magnetic fields at a sequence of frequencies in the subsonic (or audio) band and then uses inversion software to infer the soil resistivity as a function of depth.

The seismic instruments are active devices, which must be operated on the ground with imbedded sensors. In practice, the geophysicist illuminates the survey zone with vibrational energy, either impulsively or harmonically, producing thereby surface (Rayleigh), compressional (p-waves), or shear waves (s-waves), among other possibilities. The reflected, refracted or backscattered energy is recorded with geophone (or accelerometer) arrays and processed with sophisticated inversion algorithms. Despite the high cost of collecting and processing seismic data, these techniques continue as an essential tool for the exploration geophysicist.

The EM techniques are economical, non-invasive, and highly productive; and thus continue to gain in popularity. Like the gravitometers and magnetometers, EM equipment may be operated from an aircraft or on the ground. The EM sensors are active instruments, which are operated either as frequency-domain (harmonic-illumination) or time-domain (pulsed-illumination) devices. The EM devices operate in the ELF / ULF / VLF bands (30-30,000 Hz) and make use of induction fields. The frequency-domain methods sense the lateral variations in apparent resistivity; the time-domain methods develop vertical profiles of actual resistivity. GPRs operate in the HF / VHF / UHF bands (30 MHz - 3 GHz) and make use of radiation fields. The radar methods feature high spatial resolutions and non-contact operation, but may be less effective in highly conductive sites. Finally, geophysicists make important use of optical (IR, visible, UV) and radio-frequency (microwave, mm-wave) imagery, gathered passively with satellites or aircraft. Likewise, gamma ray spectrometers, operated from the air or ground, provide indications of uranium deposits, maps of radioactive wastesites, and distributions of radon contamination.

Newly emerging technologies include the Transition Zone (30 Khz -30 MHz) and USP radars; advanced signal processing techniques, some of which have been developed by the oil and gas industry at substantial expense; VETEM, Neutron Imaging, PADAR; among other possibilities. With the advanced radars, geophysicists hope to achieve depth penetrations and spatial resolutions acceptable for subsurface (10s of meters in depth) environmental and geotechnical work.

Types of Platforms:

Platforms suitable for geophysical surveys include satellites, airplanes, helicopters, and ground-based vehicles. The satellite platforms, which include civilian, military, and commercial spacecraft launched by both domestic and foreign agencies, produce imagery in the optical (IR, visible, UV) bands that can be purchased, fused, and visualized with data obtained with other geophysical sensors. The airborne platforms include both fixed-wing aircraft and helicopters. Geophysicists use the airborne platforms to carry magnetometers, gravitometers, EM sensors, GPRs, and gamma-ray spectrometers, among other possibilities. The terrestrial platforms include ground-mobile (wheeled), portable (backpack), ground-contact (skids, electrodes, vibrators, geophones), and ground-penetrating devices (penetrometers). Typically, the satellite based devices feature high productivities (square kilometers per day), but lower (>10 m) spatial resolution, except at optical wavelengths, where submeter imagery is often available. The terrestrial methods, by contrast, are far slower (acres per day), but feature excellent (down to 10 cm) spatial resolutions in both vertical and lateral directions.

3.1.1 Summary Description of Sensor Technologies

In this section, we provide an assessment of non-invasive, both existing and emerging, sensors relevant to geophysical mapping of the near-surface. In describing each sensor, we first provide a brief description of: *(1)* the technical concept underlying the measurements; *(2)* the geophysical feature the sensor attempts to investigate; *(3)* the geological value of the sensor measurements, including any of its special capabilities or applications; *(4)* the deployment technique and operations, including the productivity in a field environment; *(5)* the data processing required to render the sensor data interpretable by the human eye or fusible with other geophysical data; and *(6)* the commercial availability and operating cost of the sensor.

3.1.1.1 Magnetometry

Technical Concept:

Geophysical magnetometers measure the strength and direction of the earth's local magnetic field. The technique is a passive one in the sense that the survey site is not stimulated or illuminated with an active source, but depends on the naturally occurring magnetic fields at the earth's surface. Local variations (anomalies) in the earth's field provide geophysical clues as to the lateral (horizontal) structure of the subsurface environment. It is also possible to estimate the nominal depth of detected anomalies by ratioing the strength and gradient measurements. **Exhibit 3.1.1.1-1** and **Exhibit 3.1.1.1-2**, respectively, show a typical instrumentation and a map generated with magnetometry.

Geophysical Concept:

Anomalies in the strength and gradient of the earth's magnetic field indicate the presence of dikes, plutons, faults, sutures, and other magnetically sensitive or active products. The spatial variations in the total field provide information about the lateral position of the anomaly and the gradient indicates its depth. The lateral and depth resolutions both decrease with increasing sensor height. In addition, the depth resolution decreases with increasing anomaly depth. Although computer interpretation is sometimes applied, magnetic field data are often interpreted without computer assistance by experienced geophysicists.

Geological Value:

Terrestrial magnetometers represent an important tool for detecting buried magnetic objects, *e.g* 55-gallon drums, steel pipes, reinforced concrete, and other magnetically susceptible materials. Other applications include mapping of steeply dipping geologic contacts, detection of regions of stress amplification or geologic weaknesses, and study of ground-water resources. The aerial surveys, by contrast, provide information for ascertaining regional geology and determining the thickness of sedimentary basins.

Deployment / Operation / Productivity:

Geophysicists use both airborne and ground-based magnetometers to map their survey sites. The productivity of the aerial magnetometers is quite high (tens to hundreds of square kilometers per day), but the spatial resolution is correspondingly low (10-100s of meters). The terrestrial gear provides far more spatial detail (1-10 meters), but is less productive (acres per day). Costs for computer reduction and interpretation of the collected data are modest when compared with that used with the seismic and electromagnetic modalities.

Availability / Cost:

A wide variety of airborne (fixed-wing and helicopter) and terrestrial (ground-mobile and man-portable) magnetometers are available in the commercial marketplace. Owing to their complexities, the airborne surveys are generally conducted by specialists. Several organizations in Canada and the U.S. will conduct airborne surveys on a contract basis. Terrestrial surveys may be conducted using a rented magnetometer or by hiring a professional geophysicist with access to one. The latter approach usually entails a written interpretation of the collected data. Terrestrial surveys entail one or two operators and typically run $300 / acre. Aerial survey costs are about $5,000 per day, but can be modest when bundled with the airborne EM survey, as is often the case. Again, computer processing is nominal and geophysical interpretation typically straight-forward.

Exhibit 3.1.1.1-1: Typical Magnetometry Instrumentation

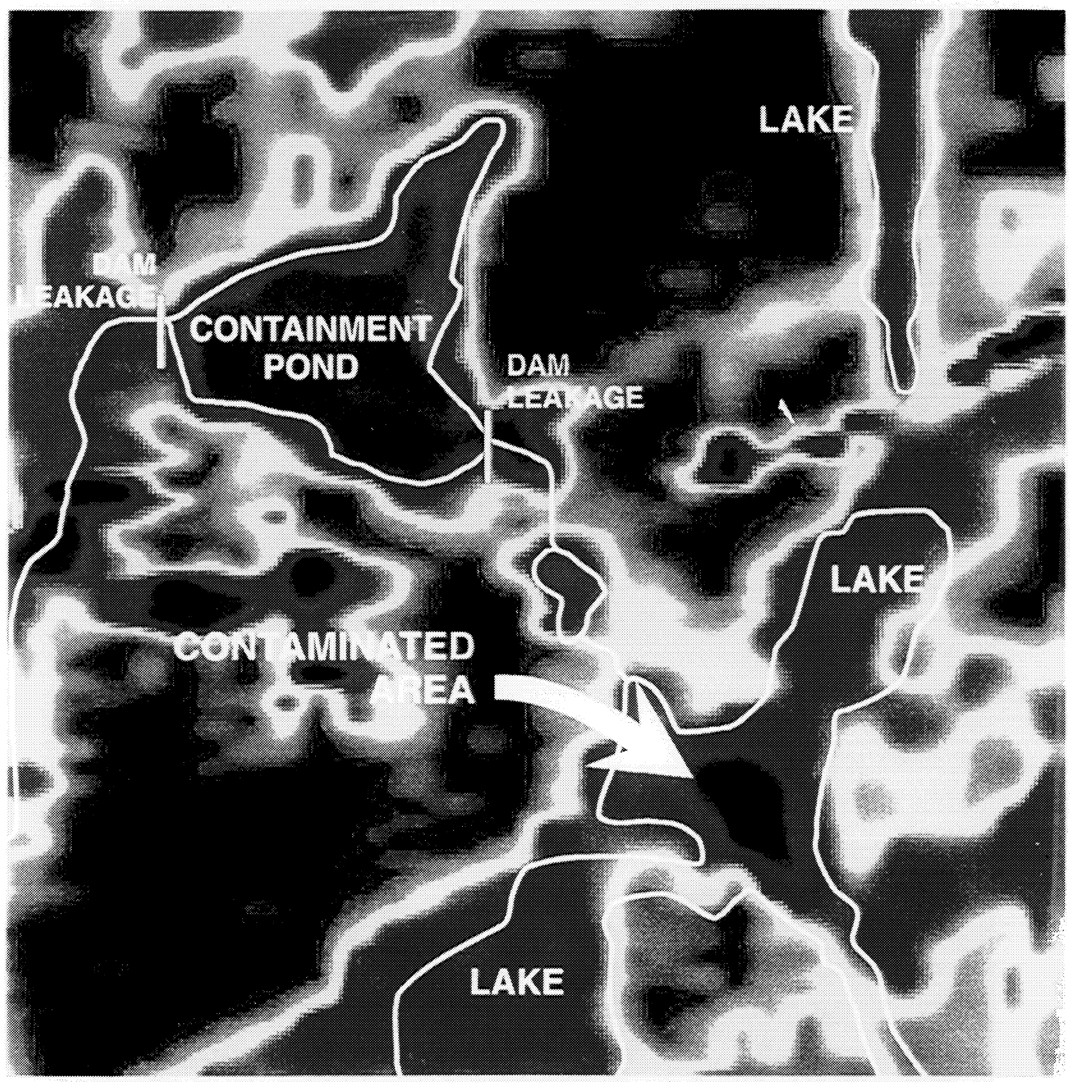
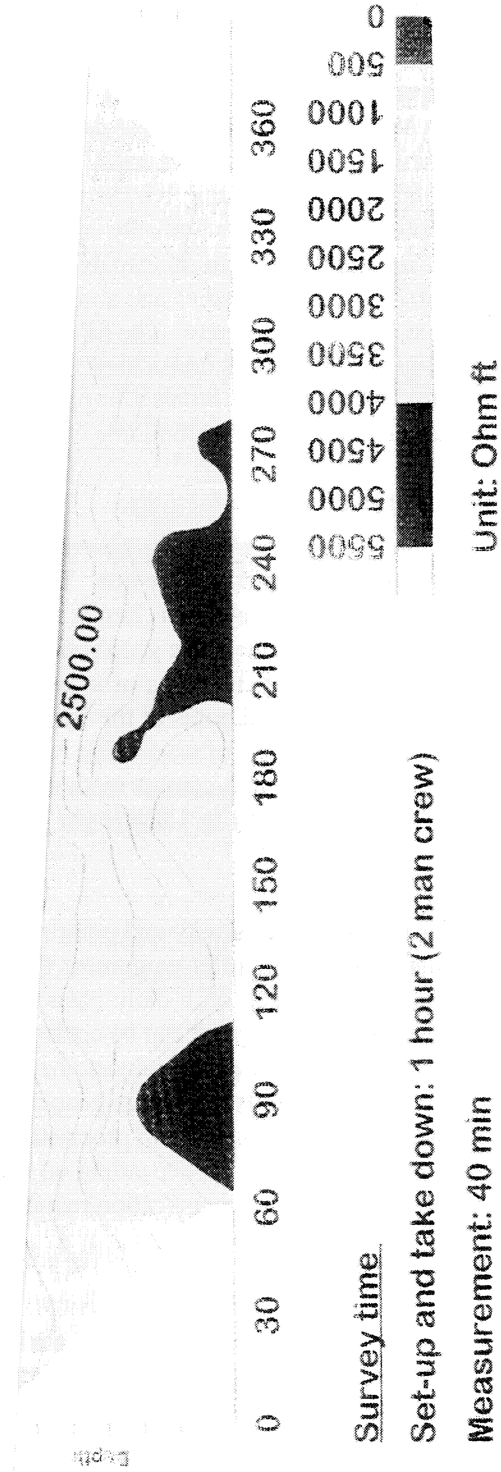


Exhibit 3.1.1.3-2: HEM Map of a Leaking Containment Pond

Exhibit 3.1.1.2-1: Typical Instrument for Resitivity Surveys (Sting 1)

.3-1: HEM Typical Uses



Survey of Karst Region

Geological Value:

Resistivity has proven effective in mapping caves, sinkholes, and underground streams in karsted regions, such as exists at the MSFC. This effectiveness derives from the technique's good spatial resolution (several meters) and its functionality in wet, conductive soils. As a rule of thumb, the spatial resolution of the resitivity method, at the depth equal to the spacing between electrodes, equals electrode spacings and becomes poorer with increasing depth. Karst regions typically entail moist limestone, air-filled caves, and pools of water; features that represent a natural match to the capabilities of the resistivity technique. The IP technique, by contrast, is more sensitive to metallic bodies and so is more suited to survey sites that might contain 55-gallon drums, metal pipes, and reinforced concrete. The SP method provides a unique approach to monitoring fluid and ionic flow underground; the latter is considered relevant in locating underground streams in a karst environment. The resistivity techniques can be used in principle for mapping subsurface under buildings with electrodes placed around the perimeter of the building.

Deployment / Operation / Productivity:

Geophysicists obtain cross-sectional images of the survey site by implanting long strings of specially designed electrodes along the designated survey line. Typically, the length of the string approximates the desired depth of penetration. When the survey line is longer than the desired depth, the electrode string is leap-frogged along the survey line. For 3D surveys, the geophysicists lay out a set of parallel survey lines. Inversion software is used to generate the 2D or 3D maps of survey site. In practice, other survey configurations are possible, depending on the geophysical goals of the survey, the capabilities of the on-site data collection gear, and the availability of data inversion software. The resistivity and polarization techniques are partially invasive and so less productive than the non-contact methods, such as FDEM or the monostatic GPR. In practice, a two-man team can survey from 0.1 to 1.0 acre per day, depending on resolution requirements and site conditions.

Availability / Cost:

Equipment for measuring resistivity and polarization is readily available and not difficult to use. Suppliers in the U.S., Japan, and Europe offer equipment that is available for immediate purchase. Alternatively, either the equipment can be rented on a daily basis from a number of geophysical supply houses in the U.S. or Canada, or a licensed geophysicist can be contracted to conduct an electrical survey, using either their own or rented equipment. In contrast to magnetometers, the collected data must be inverted with sophisticated computer software to attain its maximum geophysical value. In practice, contract geophysicists use their own software or hire processing houses with proprietary software packages for this task. With processing, the cost per acre runs at $1,000 - $5,000, depending on electrode spacing required, degree of difficulty in implanting electrodes in the soil and the sophistication required for computer processing of the data.

3.1.1.3 The EM Methods

The EM sensors are active instruments which are operated either in frequency-domain (harmonic illumination) or time-domain (pulsed illumination) modes. These devices operate in the ELF / ULF / VLF (30 - 30,000 Hz) and make use of induction fields. The frequency-domain methods sense the lateral variations in apparent resistivity; the time-domain develop vertical profiles of actual resistivity. Both sensor modalities can be operated either from airborne platforms or ground-based surveys. One well known method for airborne EM survey is the Helicopter EM (HEM), an example of which is shown in **Exhibit 3.1.1.3-1** (typical instrument) and **Exhibit 3.1.1.3-2** (a typical result). Two commonly used EM (TDEM, FDEM) techniques are described below.

Exhibit 3.1.1.3-1: HEM Typical Uses

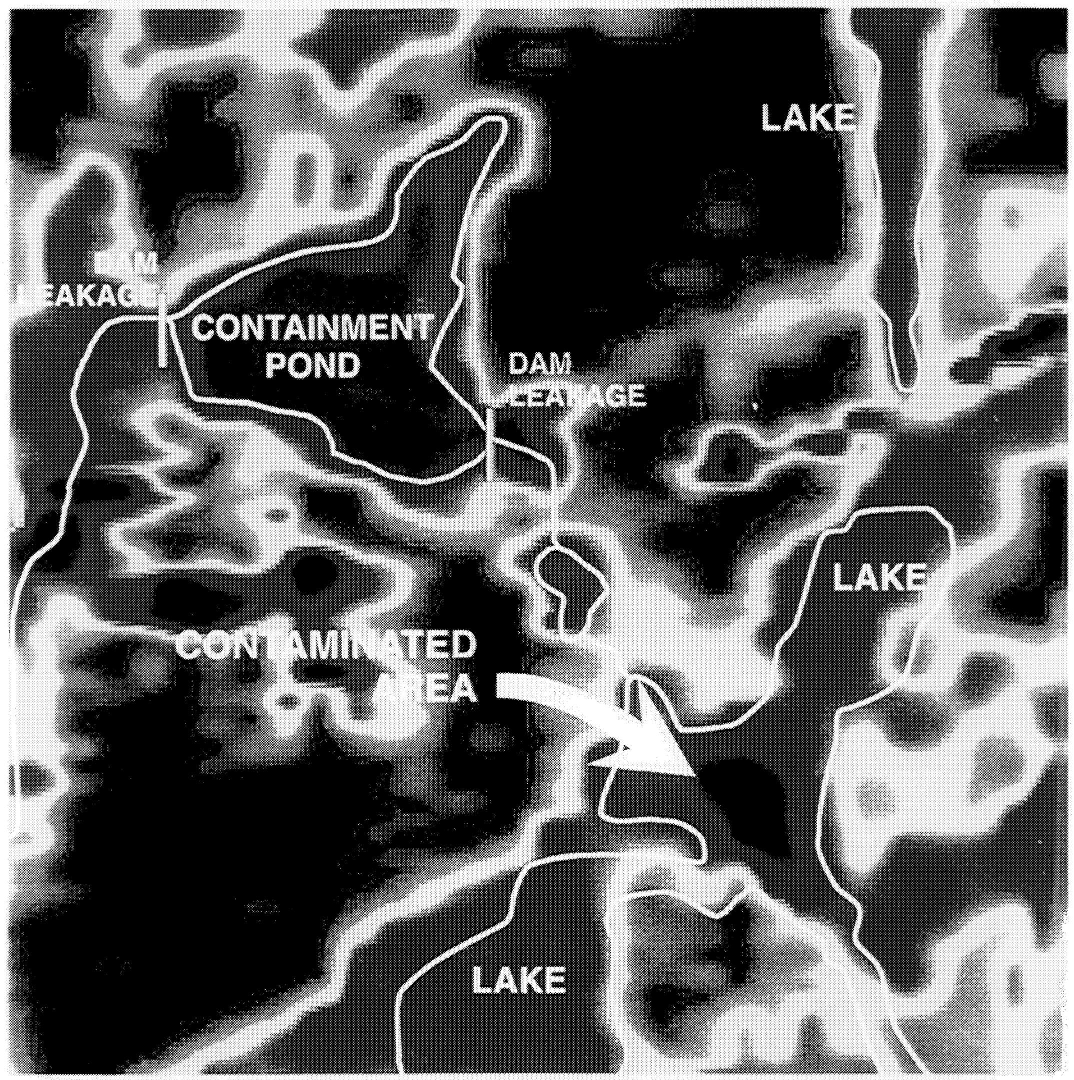


Exhibit 3.1.1.3-2: HEM Map of a Leaking Containment Pond

TDEM

Technical Concept:

This technique, which is an active one, illuminates the underground with an impulsive source of electromagnetic radiation. The impressed field induces eddy currents underground, which produce in turn secondary electromagnetic fields at the earth's surface. Owing to their low frequencies (ELF / ULF), the impressed fields are inductive, rather than radiative ones. The primary field is developed by passing an impulsive current through a wire loop placed on or carried above the ground; the secondary field is obtained by measuring the currents induced in a smaller, coaxial, secondary loop, also set on or carried above the ground. In practice, both the in-phase and quadrature phase of the secondary field are measured.

Geophysical Concept:

The magnitude and phase of the induced eddy currents provide clues as to the conductivity and dielectric constant of the survey site. These measurements, in turn, provide clues as to the geological make-up of the underground. Although ambiguities arise in relating an electrical quantity to a geologic one, borehole data or other prior information can usually reduce such uncertainties.

Geological Value:

The TDEM technique provides a non-invasive and inexpensive approach to measuring the spatial distribution of resistivity of the underground. The technique features high lateral resolution (with respect to the array dimensions) and fair vertical resolution (several layers). However, metal fences and buried pipes can interfere with the TDEM measurements. The technique is less effective in highly resistive soils, owing to proportionally smaller magnitudes of the secondary fields, where other techniques (*e.g.*, GPR) are more appropriate.

Deployment / Operation / Productivity:

As noted, the TDEM equipment may be operated in a man-portable (Slingram) mode or ground-contact mode. The former technique is used for high-resolution, near-surface investigations and the latter for lower-resolution, deeper investigations. Additionally, unlike the FDEM equipment, which provides a direct measurement of apparent resistivity, the TDEM data must be inverted by digital computer for the depth profiles. Survey rates in the Slingram mode are quite high (several acres per day), but slow in the ground-contact mode (acre per day).

Availability / Cost:

Manufacturers in Canada, the U.S., Japan, and Europe sell a variety of TDEM gear. The same equipment is also available for rent from a number of rental houses in the U.S. Owing to its greater complexity, the TDEM equipment is considerably more expensive than the FDEM equipment. Typical survey costs are of the order of $2000 / acre in the Slingram mode, and $5,000 / acre in the ground-contact mode.

FDEM

Technical Concept:

FDEM is also an active technique which uses a time-harmonic source of electromagnetic radiation to illuminate the underground under investigation. The impressed field induces in the underground eddy currents which produce in turn secondary fields that can be observed back at the surface.

The primary field is set-up by driving a sinusoidal electrical current through a wire loop. The secondary field is monitored at a nearby point by measuring the electrical currents induced in a second loop. Owing to their low frequencies the impressed fields are inductive, rather than radiative in nature. The depth of investigation is determined by frequency of oscillation and spatial separation of the two loops. For shallow investigations, the two loops are separated by a few meters and the operating frequency is in the ELF band; for deeper (10 meter) penetrations, the coil spacing is increased to 50 meters and the oscillation frequency moved to the ULF band. The former configuration is operable by a single person; the latter requires two people. **Exhibit 3.1.1.3-3 and Exhibit 3.1.1.3-4,** respectively, show a typical instrument used and information obtained therewith.

Geophysical Concept:

Dielectrics produce a secondary field that is out-of phase with the primary field; metal bodies, ionic fluids, and other good conductors produce ones that are in-phase. Accordingly, FDEM techniques can provide a means for mapping the horizontal distribution of both the dielectric and conductive media. When depth profiles are needed, the survey site is re-surveyed with progressively increasing coil spacings. The collected data are then "interpreted" with an inversion algorithm for the depth profiles.

Geological Value:

The magnitudes of the in-phase and quadrature components of the secondary field provide estimates of the resistivity and conductivity of the media explored.. Typically, the quadrature component is used to locate and map cultural-type features, such as pipelines and briny waters. Likewise, the quadrature components provide a means for mapping the natural features. When borehole or other prior data are available, the observed resistivity can be related to specific soils, minerals, and waters.

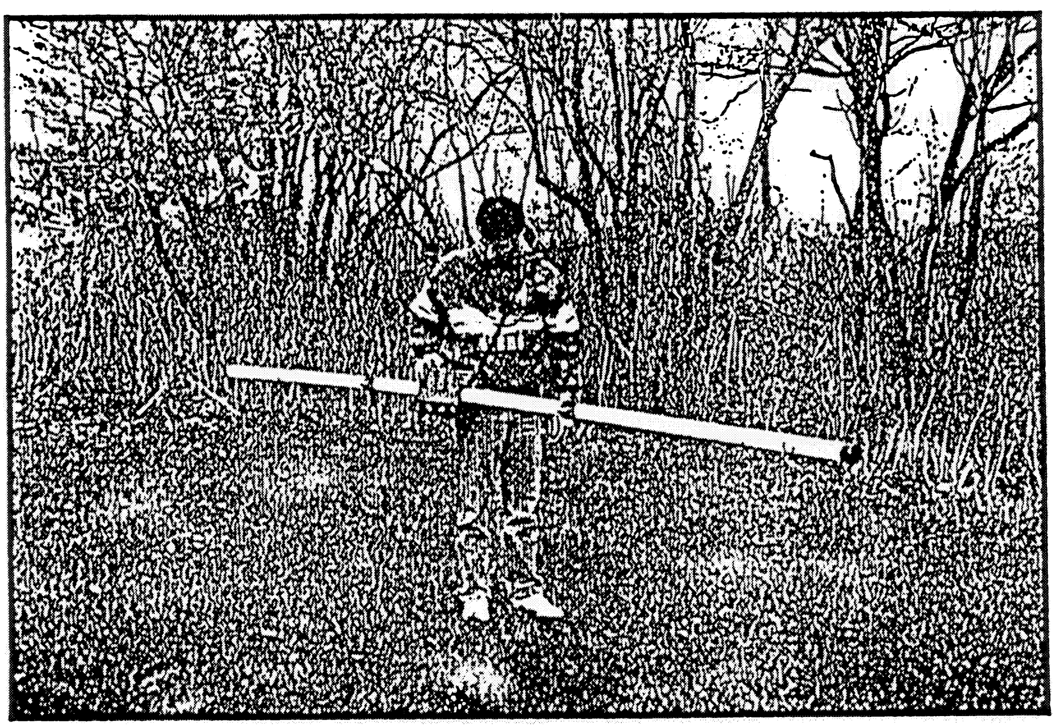


Exhibit 3.1.1.3-3: Typical Ground Portable EM (Geonics EM-31)

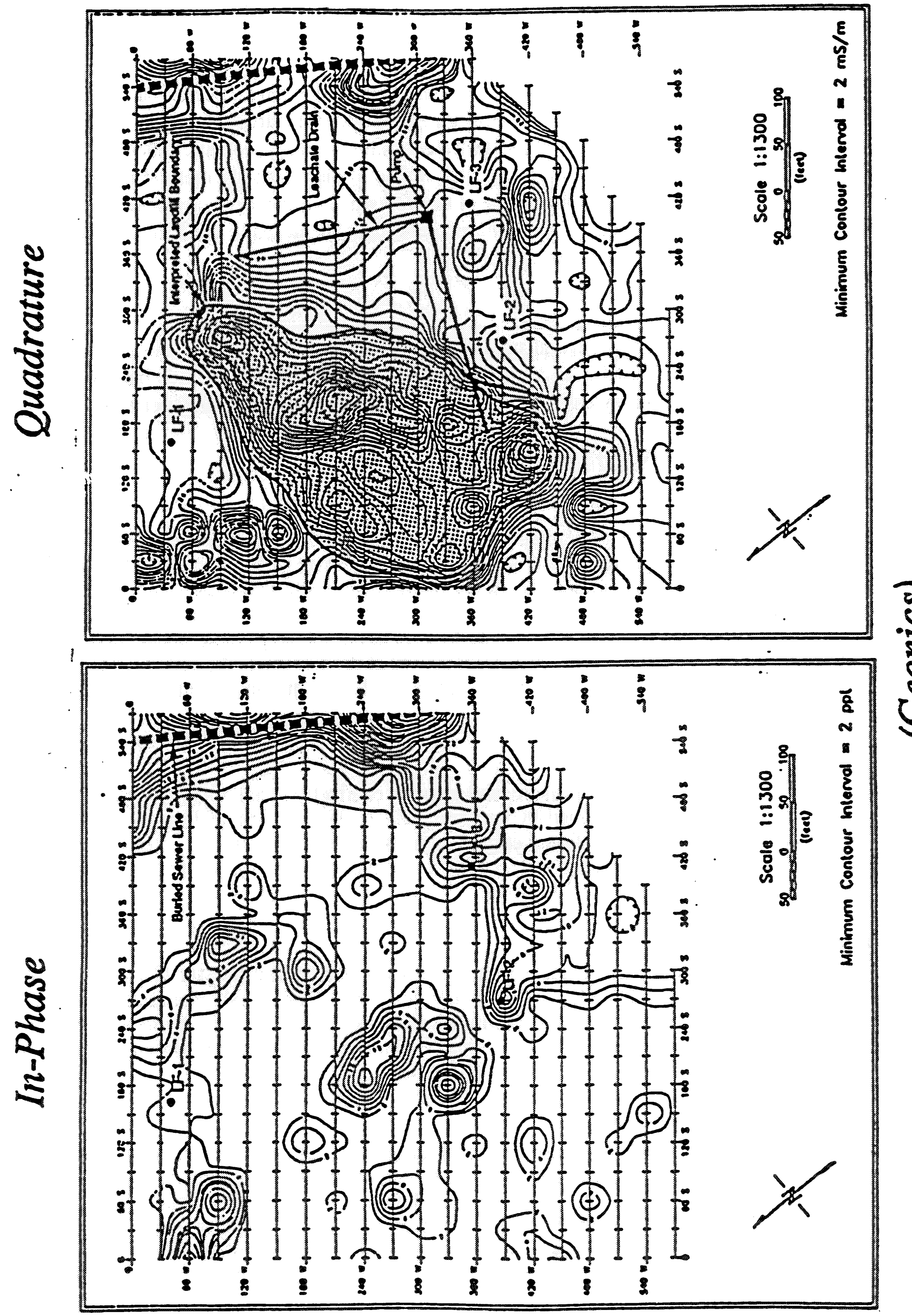


Exhibit 3.1.1.3-4: Isoconductivity Map of Leaking Basin

Deployment / Operation / Productivity:

FDEM is conducted with portable gear. In its simplest configuration, a single person carries a long pole with magnetic loops on each end. In the "Slingram" configuration, one man carries one active loop and its power supply; the other carries the receive loop and its electronics and recording package. The transmit and receive coils are close to but make no contact with the ground, unlike in the resistivity method described above. Of all the terrestrial techniques, FDEM is probably the most productive. Survey rates typically range between 3 - 5 acres per day. Only moderate levels of computer processing are required to produce quality contour maps of the resistivity and conductivity of the underground.

Availability / Cost:

FDEM equipment is available from several manufacturers in Canada, the U.S., and Japan. The FDEM equipment is cheaper than the TDEM gear, which must perform effectively over wide bandwidths. It is also available from leasing houses. Survey costs for clear sites are in the range of $1,000 per acre.

3.1.1.4 Very Low Frequency (VLF) EM

Technical Concept:

This technique is semi-active in the sense that "illuminators of opportunity" are used to irradiate the survey site. These sources are the high-powered (100 kW) VLF (20 - 30 kHz) transmitters used by the U.S. Navy to communicate with submerged submarines the world over. The electromagnetic fields produced by Navy devices are capable of penetrating the earth's surface to significant (100 meters) depths. Geophysicists investigate the geological features of the survey site by measuring the amplitude, phase, and polarization of the electric and magnetic fields produced by these transmitters at the surface of the survey site. Although VLF measurements are often interpreted directly, inversion software provides better pictures of complex undergrounds.

Geophysical Concept:

Geophysicists use VLF fields to probe, measure, and map the conductivity and dielectric constant of the near-surface geology. Data diversity is obtained by measuring the surface electric and magnetic fields at several transmitter frequencies and from several illumination directions. Near-surface dikes, contacts, and prisms may be inferred and mapped by direct study of the VLF data. Deeper or more subtle structures typically require computer inversions.

Geological Value:

VLF techniques provide a rapid and inexpensive method for investigating grosser (10 m) structure of the survey site. The technique has good depth (100 m) penetration, but lesser lateral resolutions (10 m) than other techniques. In practice, geophysicists use VLF methods to estimate surface resistivity, locate vertical contacts (*e.g.*, faults), detect water-bearing fracture zones, and map overburden coverage, and explore for minerals (*e.g.*, Sulfides).

Deployment / Operation / Productivity:

Because the VLF technique entails no illuminator and no ground contact, this technique remains the most popular of the EM modalities. Its chief drawback from an operational viewpoint is the unpredictability of the Navy transmitters, which are subject to both occasional failure and periodic maintenance. Because the positions of the Navy transmitters are fixed, illumination geometries and / or signal levels may prove unfavorable for a specific survey site. Also, interpretation of VLF measurements is not trivial and requires significant professional expertise, and some sophistication in computer processing. Because the technique entails no ground-contact, it is more productive (ten acres per day) than the multistatic (*e.g.*, seismic) or ground-contact modalities (*e.g.*, resistivity).

Availability / Cost:

VLF equipment is manufactured by several organizations in Canada, the U.S., Japan, and Europe. It can also be leased from a number of geophysical rental houses in the U.S. Due to the simplicity of both the equipment (no illuminator) and the operating protocol (quasi-monostatic), and non-contact nature of the sensor, the VLF survey costs are about $500 / acre.

3.1.1.5 Magnetotellurics

Technical Concept:

A relative of VLF, this technique entails both active and passive illumination and both near-surface and deep-sounding configurations. For hydrogeological applications, geophysicists use near-surface (10 - 100 m) configurations and active sources of ULF / VLF / LF illumination. In operation, the survey site is stimulated with a pair of meter-sized orthogonal loops driven at audio/ultrasound frequencies between 1 - 100 KHz. Electric dipoles and magnetic loops are then used to measure the secondary electric and magnetic fields along a survey line several skin depths distant. Sophisticated inversion algorithms are used to convert the collected data to cross-sectional views of the survey site. Examples of a typical magnetotellurics instrument and a map obtained therewith are, presented in **Exhibit 3.1.1.5-1** and **Exhibit 3.1.1.5-2** respectively.

Geophysical Concept:

As with the other EM modalities, magnetotellurics provides cross-sectional maps of the conductivity and dielectric constant of the survey site. 3D maps can be developed by raster scanning the survey site. It differs from the FDEM techniques in that it collects multistatic, rather than monostatic, data and measures both components of the secondary electric and magnetic fields. Because magnetotellurics uses more frequencies and wider spatial separations, its depth of penetration is also greater than the FDEM technique.

Geological Value:

Although magnetotellurics has wide application in geophysical study, the near-surface version of the technique was developed specifically for hydrogeological and environmental studies. It particular, the technique has been used to explore for ground-water, map aquifers, and delineate salt-water intrusion. Other applications include mineral exploration, bedrock sounding, and porosity surveys.

Deployment / Operation / Productivity:

As noted, magnetotellurics entails a pair of illumination loops, a pair of electric-field sensors, and a pair of magnetic-field sensors. In operation, the former remains stationary while the latter are leap-frogged down the survey line, which is called a quasi-monostatic survey configuration. Accordingly, magnetotellurics is faster than resistivity, seismic and the fully multistatic GPR, but slower than the monostatic methods like magnetometry, FDEM and monostatic GPR. In practice, two people can survey a clear three-acre site in one day, provided surface conditions are reasonable.

Availability / Cost:

Near-surface magnetotellurics is an evolving geophysical modality. As such, field-oriented equipment is limited in availability and the best inversion software is held proprietary. Geometrics (Sunnyvale CA) sells and rents a near-surface device and EMI (Berkeley) will license use of its inversion software. Owing to its newness a limited number of geophysicists are competent in the near-surface version of the magnetotelluric technique. Alternatively, a three-day tutorial in the use of their equipment and EMI software is available from Geometrics. Survey costs run higher than the average at $1000 / acre, including the cost of data inversion.

Exhibit 3.1.1.5-1: Field Setup for Electrical Conductivity Imaging System

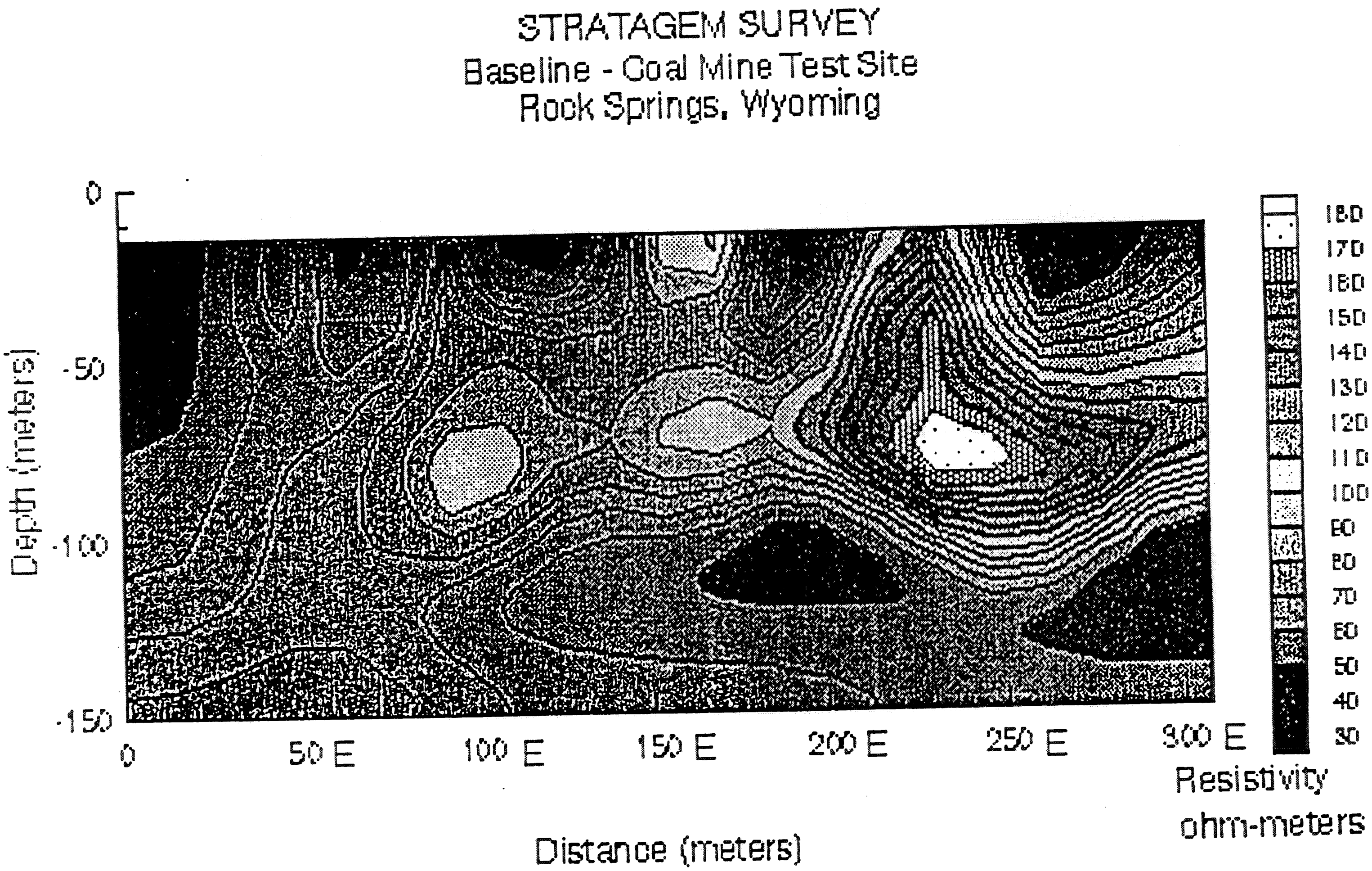


Exhibit 3.1.1.5-2: Typical Map Obtained Utilizing Magnetotellurics Instrument

3.1.1.6 VETEM

Technical Concept:

This technique is designed to measure the conductivity and dielectric properties of the topmost layers of the survey site. The VETEM technique represents an extension of the TDEM and FDEM concepts to the MF and HF bands (300 KHz to 30 MHz). In this band, typical soils are neither purely conductive nor purely dielectric; likewise, the governing equations are neither purely diffusive nor purely radiative. The VETEM equipment is designed to investigate soil properties in the depth range not covered by conventional EM methods or the conventional GPRs. The VETEM technology represents an effort to bridge the gap between these modalities.

Geophysical Concept:

As with the EM techniques, VETEM attempts to measure, profile, and map the electrical conductivity and complex dielectric constant of the survey site. In practice, both time-harmonic and impulsive illumination are used to illuminate underground. Upon inversion, the VETEM technique provides the geophysicist with geoelectric profiles at near-surface depths. The latter can in turn be related to geologic makeup of the underground, especially when borehole or other ground-truth is available for reference.

Geological Value:

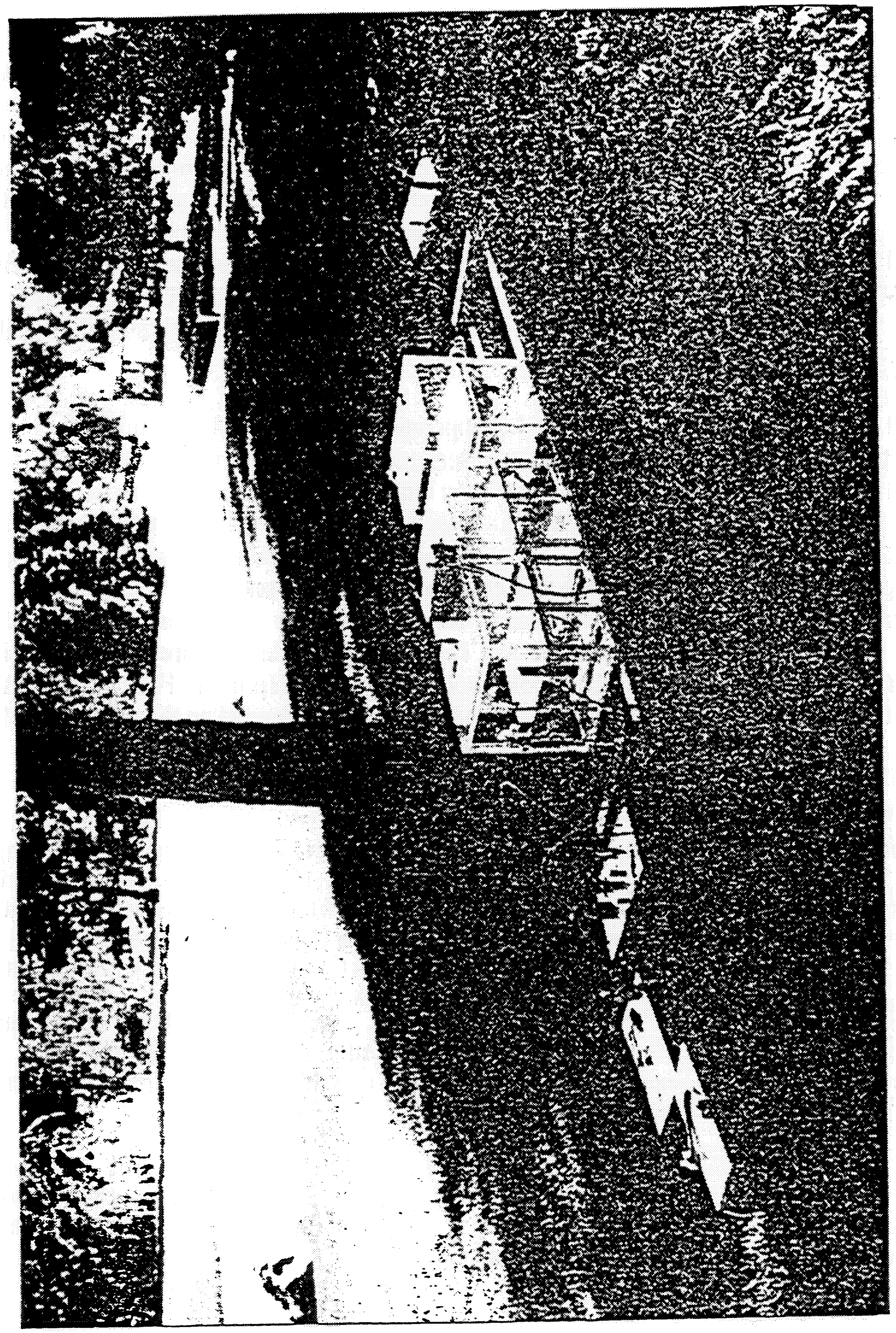
As noted, the VETEM technique is designed to investigate the region, typically in the depth range of 1 - 5 meters. This zone is of especial interest for environmental investigations. That is, wastesite and chemical plumes often exist at these depths. Moreover, by measuring both conductivity and complex dielectric constant, the geophysicist can sometimes infer the chemical nature of the detected contaminants.

Deployment / Operation / Productivity:

Like the EM methods, the VETEM technique illuminates and observes underground sites with a pair of decimeter-sized loops separated by meter-sized distances. The optimum separation depends on the desired penetration depth and the local soil properties. Because the field measurements are taken in the transition zone, the inversion software is complex and thus expensive to process the collected data. Currently, a wheeled cart is used to carry the VETEM equipment about the survey site. Productivity is not particularly high: 1 - 2 acres per day in a cleared environment and much less in a wooded one.

Availability / Cost:

VETEM is the newest of the electromagnetic modalities. The U.S. Department of Energy (DoE) is sponsoring the development of the VETEM concept as part of its need to characterize and remediate its many wastesites. A prototype VETEM instrument is shown in **Exhibit 3.1.1.6-1**. Currently, neither the VETEM hardware nor its inversion codes are being sold in the commercial marketplace. However, DoE has mandated that the VETEM consortium make every effort to export the VETEM technology to other branches of the federal government, as well as the commercial sector. In particular, VETEM officials have expressed genuine interest in the CTS at the MSFC and, with appropriate approvals, could be willing to survey portions of the CTS as a part of their technology transfer obligations.



A prototype very-early-time electromagnetic (VETEM) system developed by the USGS.

Exhibit 3.1.1.6-1: A Prototype VETEM Instrument

3.1.1.7 GPRs

Technical Concept: GPR is an active modality that illuminates and observes the survey site using electromagnetic energy in the VLF / UHF bands (30 MHz - 3 GHz). GPRs can be used in either monostatic or multistatic configurations with ground-based or airborne (aircraft, helicopter) platforms. Compared with the electrical, EM, and seismic modalities, ground-based GPR features high (decimeter-type) spatial resolutions. With advanced methods of processing (*e.g.*, synthetic-aperture processing) of the collected data, airborne GPRs can feature similar resolutions. The penetration depth is generally sensitive to soil properties and can vary significantly from site to site. Recent advances in GPR technologies include: the *(1)* Transition Zone (TZ) Radar, *(2)* USP Radar, and *(3)* improved signal processing algorithms. **Exhibits 3.1.1.7-1** and **3.1.1.7-2**, respectively, show an example of a ground-based monostatic GPR.. **Exhibits 3.1.1.7-3** through **3.1.1.7-7** show several other examples of the range of applications of GPRs. Additional examples of GPR technologies are presented in **Section 3.2**.

TZ Airborne Radar: This radar, planned for operation in the 1 - 3 MHz band where neither conduction nor displacement currents dominate, could provide deep ground penetration. For comparable soils, the penetration capability of this radar can be expected to be about ten times greater than for conventional airborne radars such as offered by AES (250 - 750 MHz), and about three times better than that of the Carabas (20 - 90 MHz) radar. The TZ Synthetic Aperture Radar (SAR) can be expected to have important applications in imaging that include: *(a)* underground regions for environmental purposes; *(b)* underground facilities for non-proliferation; and *(c)* underground buildings for bomb damage assessment, among other possibilities. For an application to the MSFC site, effort will be required to select an operating band (MF / HF), antenna configuration (magnetic loop, electric dipole, modulation scheme (pulsed / FM), and operating platform (fixed wing, helicopter). Choices among these options would in part depend on the properties of the soil at the site.

The USP Radar:

The USP radar, discussed in Appendix III, is an improved version of the impulse GPRs and provides two capabilities not available in other designs: *(a)* RF pulses crafted to obtain optimum propagation and matched to both the medium and target and *(b)* RF pulses which are shorter in duration than the relaxation time of the medium. Under certain well-defined conditions, it is expected that significant penetration will be obtained through media normally absorptive or dispersive. A rule of thumb for Continous Wave (CW) signals is that the attenuation of electromagnetic radiation rises with frequency and that at a given frequency wet materials exhibit a higher loss than dry ones. In the present instance, impulse, not CW, signals are addressed, and it is expected that there are major differences between CW, Frequency-Modulated Continuous Wave (FMCW), stepped FM and impulse signals (Barrett, 1991). Unfortunately, the overwhelming amount of data on dielectric effects has been obtained with CW signals, so impulse effects with pulses shorter than the relaxation time of the material are seldom available.

The monostatic equipment differs from the multistatic (multi-offset) hardware. Unlike for the multistatic GPRs, the transmit and receive antennas in monostatic radars are co-located (or nearly co-located). Relative to the multistatic ground-based modalities, the monostatic GPR features higher mobility and productivity, but are considerably more susceptible to noise and clutter.

Geophysical Concept:

Under the reflection model, radar returns are produced by dielectric or conductive contrasts underground. As in reflection seismography, such contrasts are highly correlated with the interfaces between one geological region and another or between rocks, fractures, lenses and other anomalies and the surrounding underground. Additionally, GPRs operate at much shorter wavelengths, and hence feature much higher resolutions than the

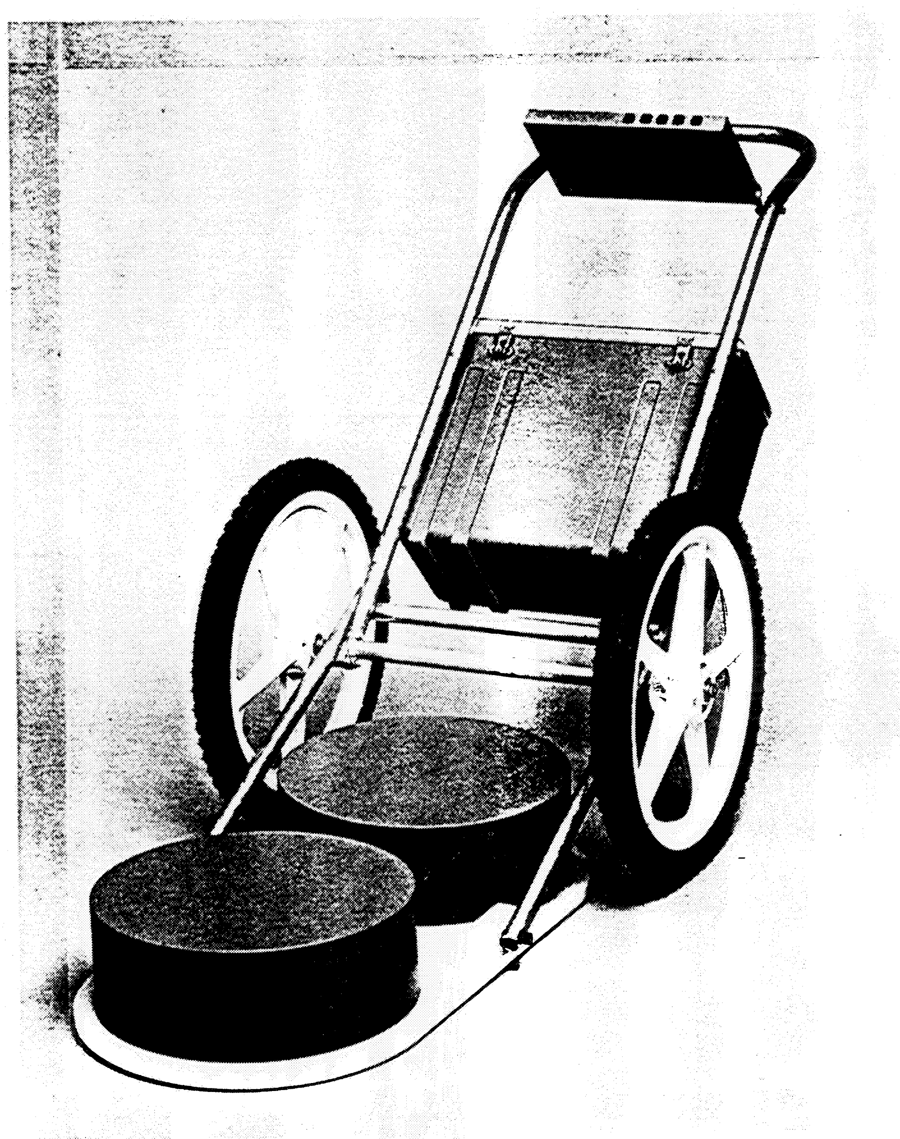


Exhibit 3.1.1.7-1: Example of a Ground-Based Monostatic GPR (GeoRadar)

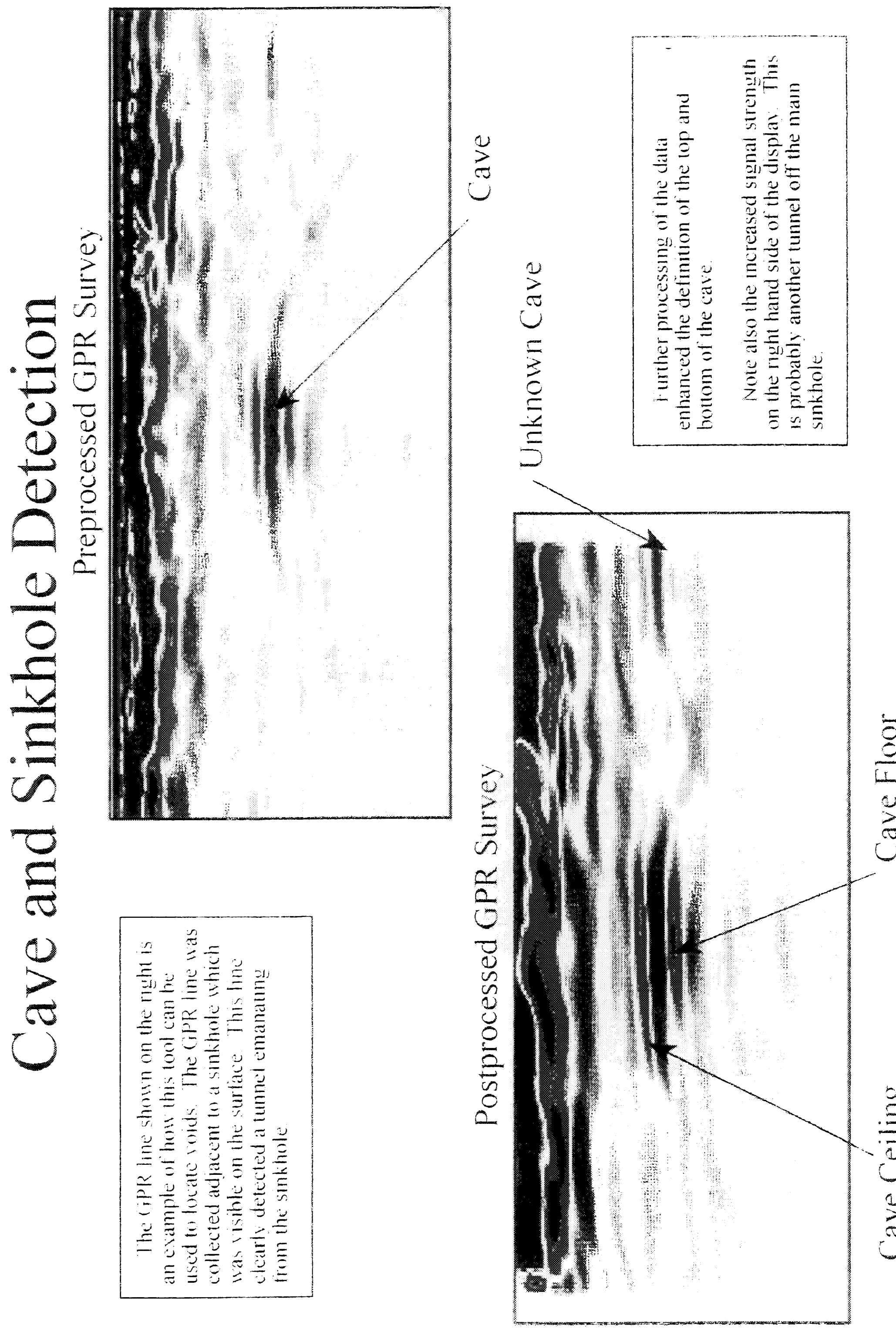
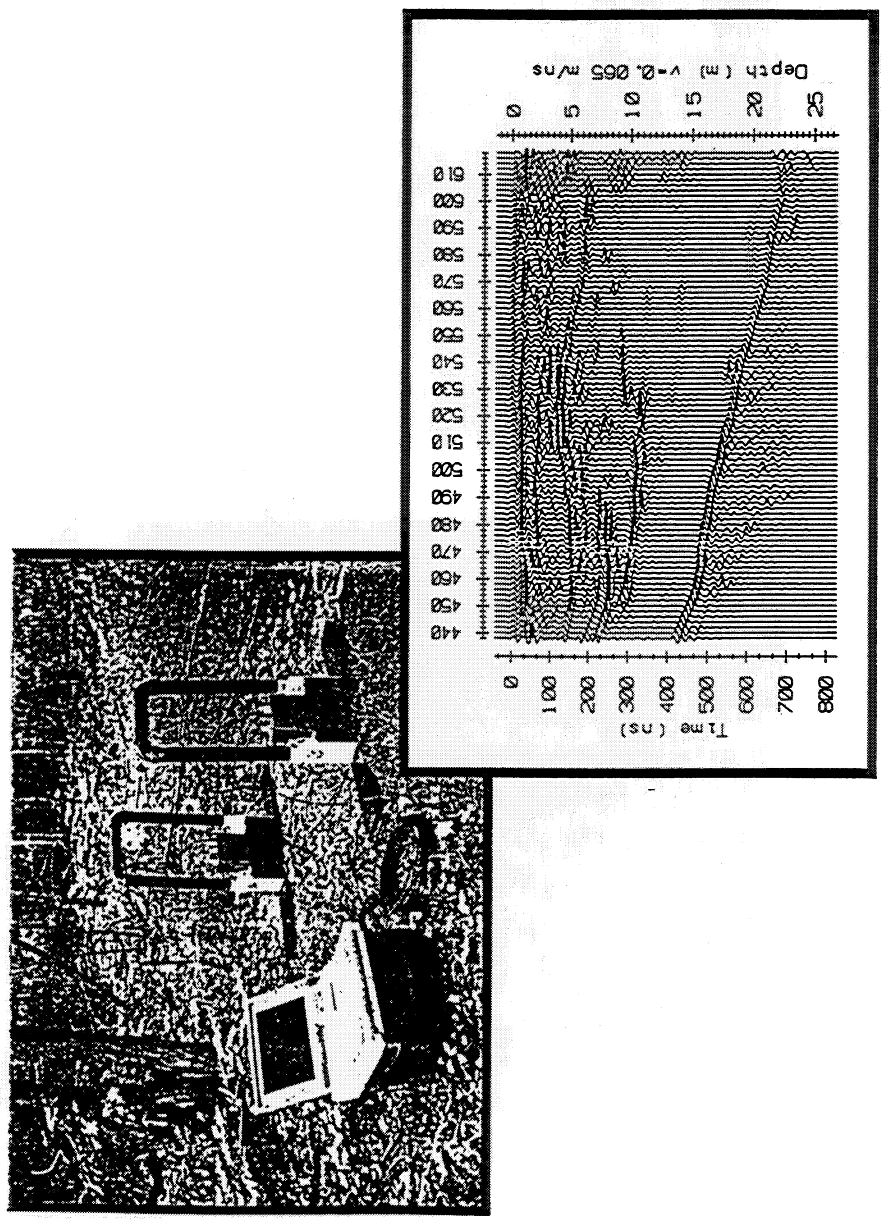
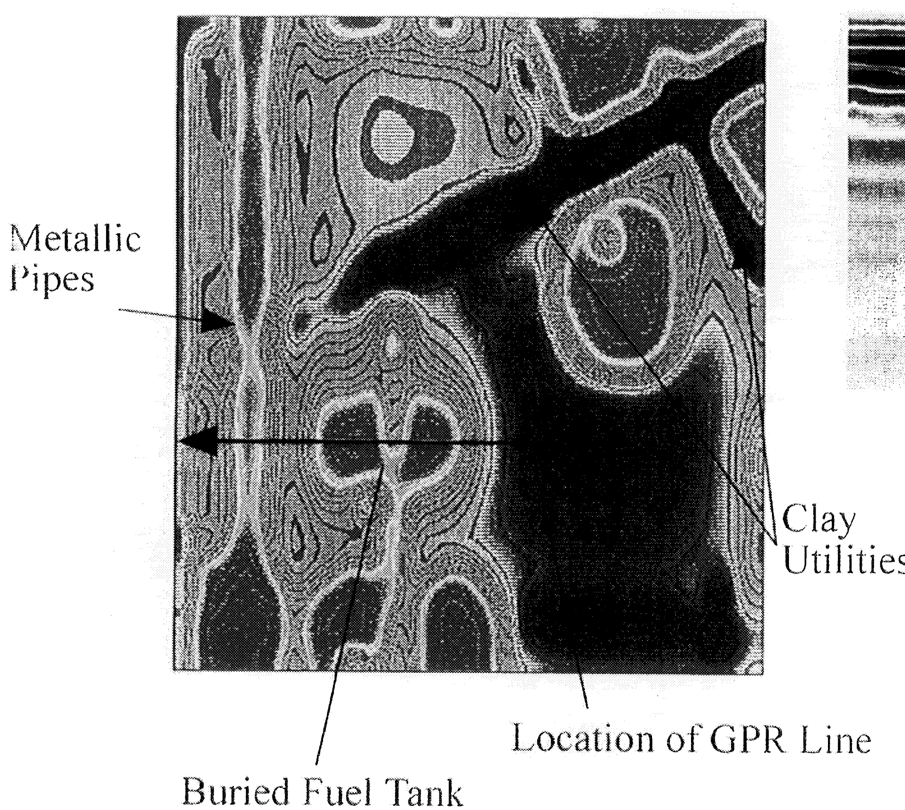


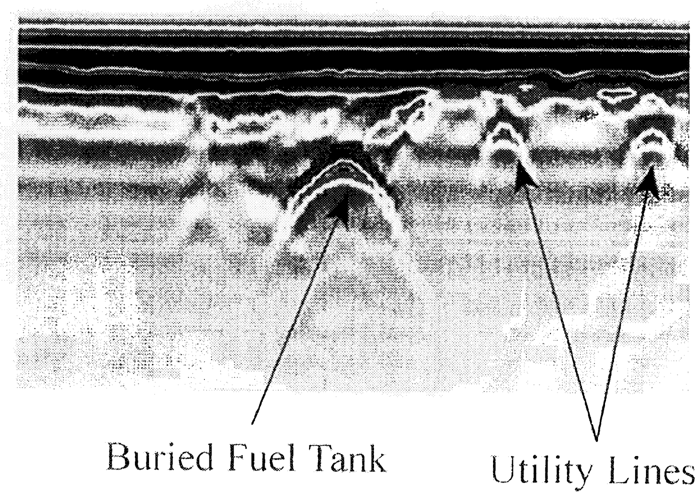
Exhibit 3.1.1.7-2: Cave and Sinkhole Detection with GPR (Radian Geophysics)



Exhibits 3.1.1.7-3: Another Example of the Range of GPR Applications

Fuel Tank Under A Parking Lot

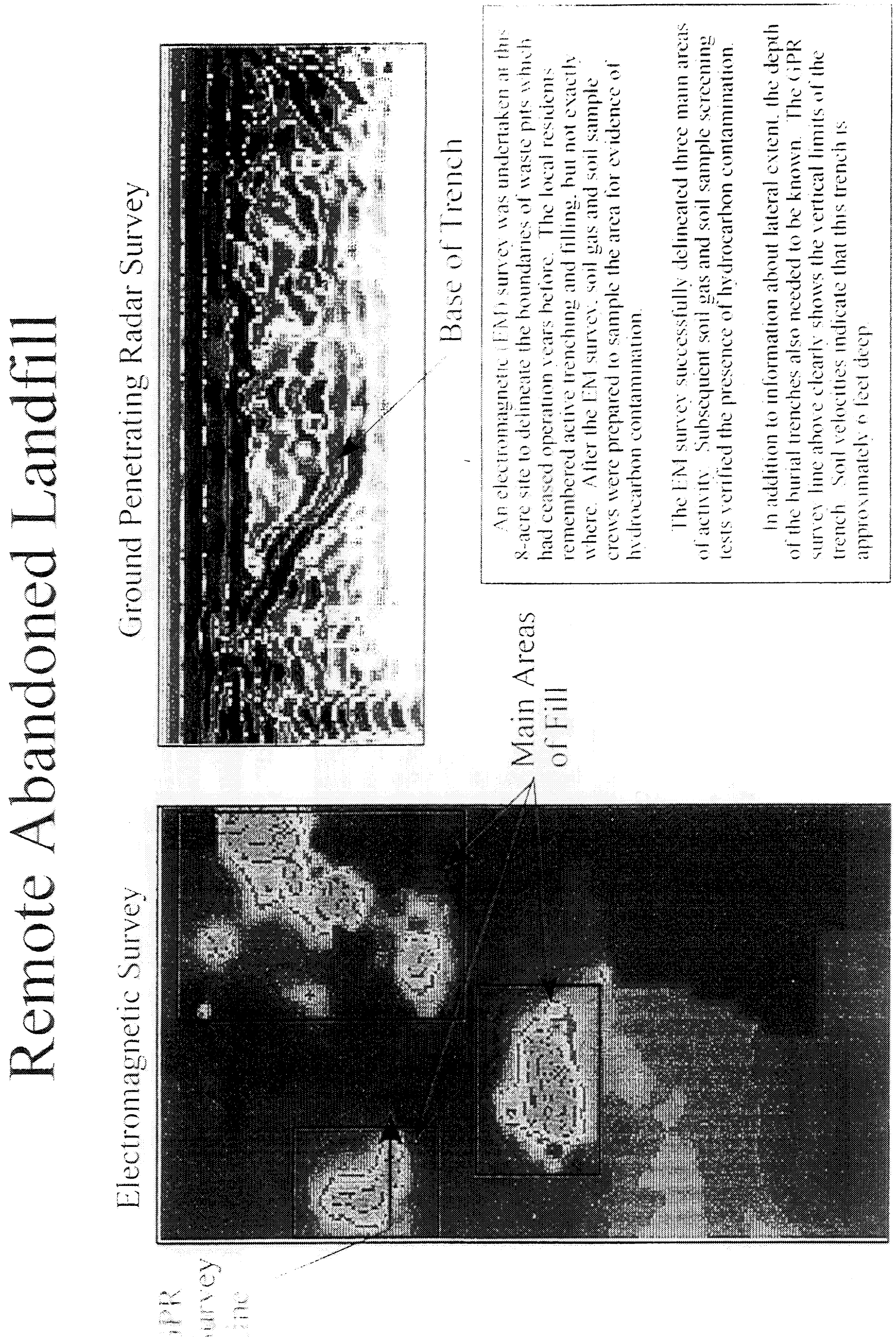




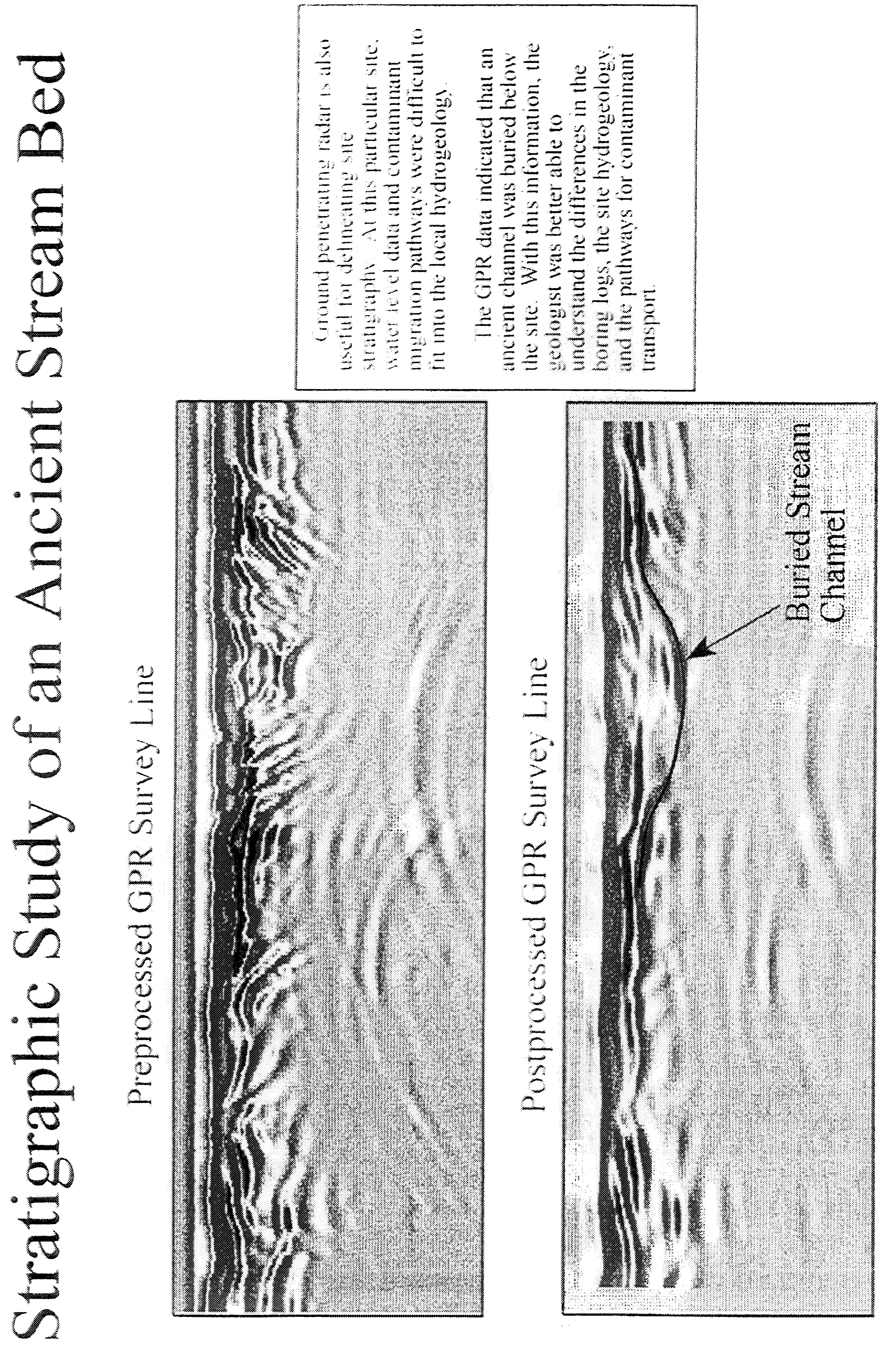
The electromagnetic survey was conducted at this 150-foot by 150-foot site to locate all metallic objects. The fuel tank and utility lines were the only metallic objects that appeared on the survey which could not be attributed to above ground interference. Additionally, the dark blue linear features labeled "Clay Utilities" were successfully defined from the electromagnetic survey.

Upon completion of an initial field interpretation of the electromagnetic data, a ground penetrating radar survey was conducted to determine the depth and lateral extent of the fuel tank. The survey succesfully located the tank and in addition confirmed the presence of other utilities.

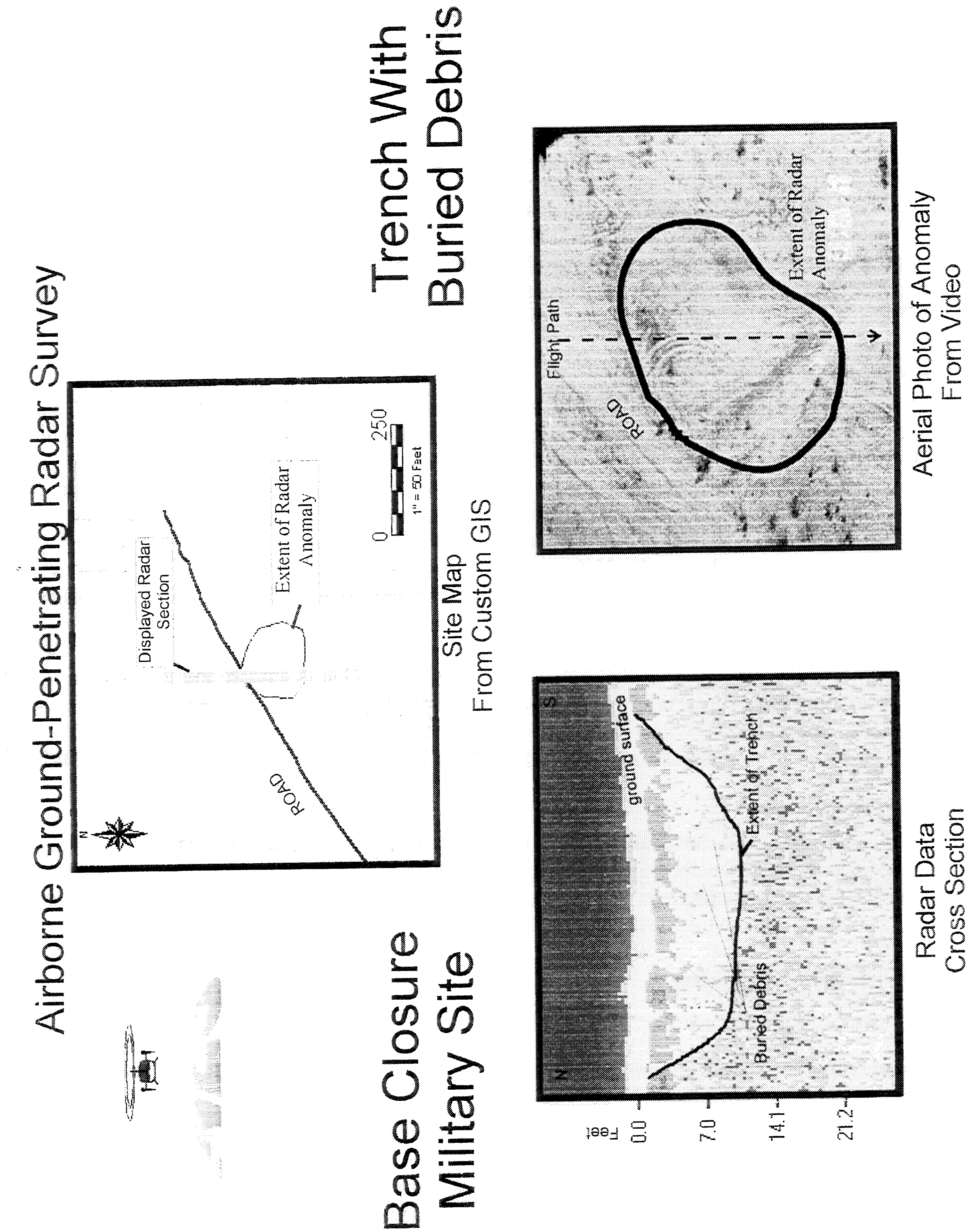
Exhibits 3.1.1.7-4: Another Example of the Range of GPR Applications



Exhibits 3.1.1.7-5: Another Example of the Range of GPR Applications



Exhibits 3.1.1.7-6: Another Example of the Range of GPR Applications



Exhibits 3.1.1.7-7: Another Example of the Range of GPR Applications

seismic or EM modalities. Accordingly, GPR provides an important means for imaging both the global structure and isolated features of the survey site at high lateral and vertical resolutions.

Geological Value:

In favorable soils, GPRs can readily image the underlying stratigraphy, natural artifacts (rocks, voids, faults), cultural artifacts (buried pipes, 55-gallon drums), archaeological artifacts (foundations, gravesites), waste sites, and contaminant plumes. Detection and mapping of karst features is a common application of GPR. Limestones generally exhibit relatively low radar signal attenuation (1 - 3 dBm). Cavities that are filled with water or air feature dielectric contrast and hence produce a strong radar return. Other applications include high resolution mapping of alluvial and glacial deposits under lakes and rivers, near-surface stratigraphic mapping, and characterization of water- bearing fractures in intact rock.

Deployment / Operation / Productivity:

For ground-based GPRs, the manufacturers use sleds and wheeled platforms to carry the GPR equipment across the survey sites. Although direct ground contact is not required for GPR, energy coupling improves dramatically as the earth is brought into the evanescent zone of the transmit and receive antennas (approximately one-sixth wavelength). Also, at least one manufacturer (GeoRadar) sells a man-portable system, which is especially suitable for rough terrain. In operation, the geophysicist pushes, drags, or carries the radar system across the survey site and a transect of the underground is produced in real time. By laying out parallel survey lines, the geophysicist can develop a 3D map of the survey site. Survey speeds are high by terrestrial standards, with coverage rates on the order of three acres per day in cleared areas and one acre per day in cluttered (wooded) ones.

For airborne GPRs, two types of platforms are typically used. One is aircraft and the other a helicopter. Systems are provided with GPS and some on-board processing capability. In addition, geophysicists carry video equipment on the same platform to produce site topographic maps. Moreover, magnetic and EM equipment can be easily incorporated on the same platform enabling rapid surveys with multiple sensor types.

Availability / Cost:

GPR equipment is manufactured and sold by American, Japanese, and European companies. This equipment can also be leased from a number of geophysical survey houses. GPRs are not particularly difficult to use in the field and the support software is well automated. Accordingly, the cost per acre typically runs from $500 - 2,000 / acre, depending on the site conditions and the details of the information required.

3.1.1.8 Optical-Style Imaging

Technical Concept:

Overhead (airborne / spaceborne) techniques, together with physical inspection at the ground level, represents a traditional approach to gaining an initial picture and understanding of the survey site. In practice, both satellites and fixed-wing aircraft are used as survey platforms and geophysical imagery is gathered in the microwave, mm-wave, IR, visible and UV bands. Typically, video cameras are used in the near-IR through UV bands, while line scanners are more often used in the far-IR and microwave bands. Depending on platform altitudes, numerical aperture, and radiation wavelength, spatial resolutions can vary from several centimeters to several meters, or more.

Geophysical Concept:

Visible and UV imagery provide direct clues as to the spatial, compositional, and geological character of the survey site. The IR sensors can estimate surface temperature, while the mm-wave and microwave bands can estimate temperature as a function of depth (after computer inversion). Additionally, under suitable conditions, the microwave technique can also penetrate foliage, snow, and ice.

Geological Value:

Overhead imagery provides a large-scale picture of the survey site. Mountains, meadows, moraines, rivers, volcanos, major underground faults, and minor surface faults are generally visible in such imagery. Temperature differences, whether induced meteorologically or geologically, are readily inferred from overhead imagery. Also, local hydrogeological features such as sinkholes, artesian wells, and springs, are often identifiable. Natural tree lines, which are sometimes associated with seasonal creeks and water-bearing faults, provide more subtle clues as to the underlying hydrogeology. And, cultural objects, such as buildings, roads, and tilled fields, are readily identified and mapped using aerial techniques.

Deployment / Operation / Productivity:

Aerial imagery is obtained by flying an instrumented aircraft over the survey site. Aside from certain weather conditions, aerial surveys are straight-forward operationally. Satellite imagery is obtained from existing archives or by contracting with government, private, or foreign organizations planning new launches. Both methods feature extremely high productivities (square kilometers per hour) when compared with the ground-based modalities.

Availability / Cost:

Overhead photographs taken in the UV, visible, and near-IR are readily available (for a fee) from previous aerial surveys or may be obtained by hiring a survey company with an instrumented aircraft. The UV, far-IR, mm-wave, microwave imagery is more difficult to obtain since few organizations outside government support these modalities. Satellite data is also available in archive form, either in public domain (as in the U.S.) or on a fee basis (as in France). In addition, the Russian government will survey at a designated site anywhere in the world at 2 - meter resolutions in both IR and visible bands. Costs for aerial imagery typically runs $1,000 per square kilometer (250 acres) for aerial imagery and probably lower for satellite imagery.

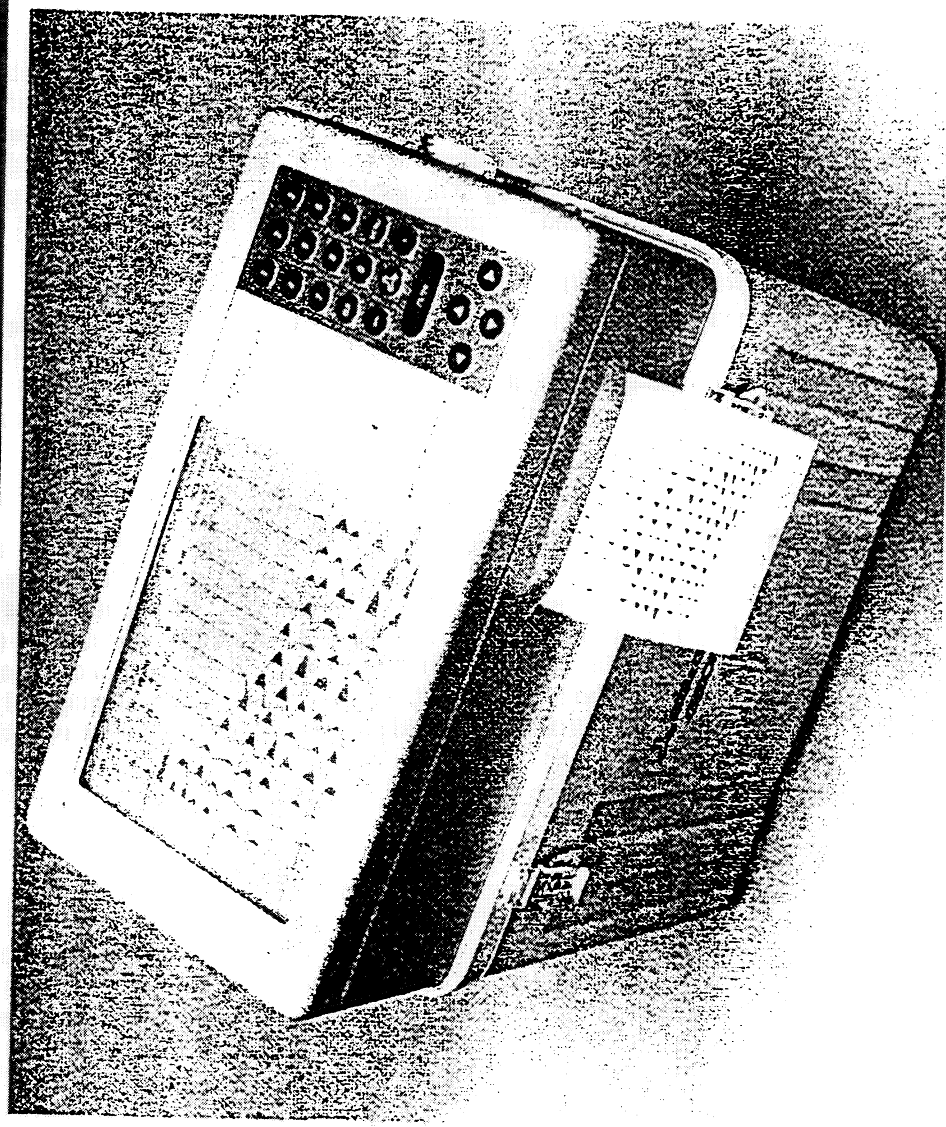
3.1.1.9 Reflection / Refraction Seismics

Technical Concept:

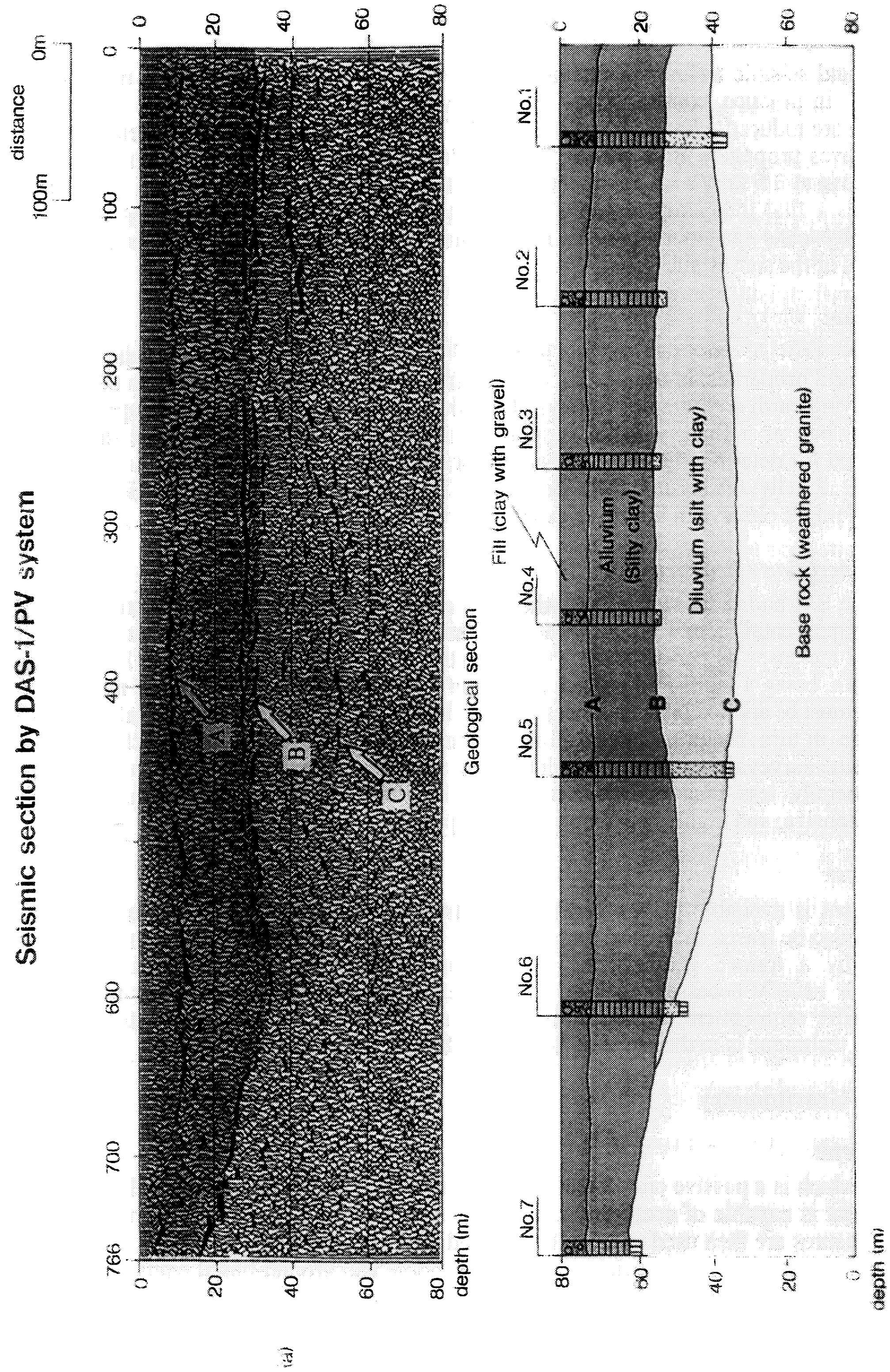
These techniques employ mechanical vibrations to probe and image underground environments. Both stepped-frequency and impulsive sources are used to introduce energy into the ground. And, both geophones (velocity sensors) and accelerometers (acceleration sensors) are used to record the returned energy. Environmental studies make important use of both reflection and refraction methods. The reflection technique, which is used for deeper studies, views the underground as a collection of discrete scatterers (rocks, faults, voids) sitting in a distinctly layered geologic environment; the refraction technique, which is used for shallower studies, models the underground as a layered environment, but also allows for velocity gradients within the individual layers. When the underground is distinctly layered and deeper probes are called for, geophysicists gravitate to the reflection techniques. When the underground entails velocity gradients and near-surface studies are needed, refraction methods are more favored. Both modalities make intensive use of computer processing and computer visualization. Joint inversion of reflection and refraction data is sometimes undertaken, especially for near-surface studies. **Exhibits 3.1.1.9-1** and **3.1.1.9-2** present, respectively, examples of a typical seismograph and a map obtained therewith.

Refraction/Reflection Seismograph

(Geometrics)



Exhibits 3.1.1.9-1: Typical Refraction / Reflection Seismograph (Geometrics)



Exhibits 3.1.1.9-2: Near-Surface Seismic Section of Alluvial Basin (OYO DAS-1 / PV)

Geophysical Concept:

The reflection and seismic techniques attempt to measure propagation velocity as a function of depth and lateral position. In practice, compressional waves (p-waves), shear waves (s-waves), and Rayleigh waves (surface waves) are induced, observed, and measured. The p-waves move at high speeds, while the s-waves and Rayleigh waves propagate more slowly. Wave velocity also varies importantly with rock and soil type, *e.g.*, p-waves move at 3.5 km / s in granite, but only 1.0 km / s in unconsolidated sand. Accordingly, seismic velocity provides a first indication of geological structure. In addition, by comparing p-wave and s-wave velocities, geophysicists can infer Possion's ratio, Young's modulus, bulk modulus, and shear modulus for successive layers of the survey site.

Geological Value:

Seismic techniques provide cross sections and maps of the stratigraphy and mechanical character of the survey site. The mechanical properties, in turn, of the underground provide important clues as to the geological make-up of the underlying earth *e.g.*, granite vs sand. Likewise, water will support both compressional waves and Rayleigh waves, but, as a fluid, will not support s-waves. Accordingly, the seismic methods provide an important method for determining whether sand, water, air, or another material fills the interstitial spaces in a given material. Finally, the seismic methods provide 2D and 3D imagery that most closely resembles what the geophysicist might observe in boring or excavation of the survey site.

Deployment / Operation / Productivity:

In contrast to the EM and radar techniques, which are essentially non-contact, the seismic methods, like the resistivity technique, entail actual ground contact. This limitation complicates the survey task, reduces its productivity, and increases its per-acre cost. The collection of Common-Midpoint (CMP) or Common-Depth Point (CDP) data, being a multi-fold procedure, further magnifies the survey time and its dollar cost. Also, static corrections must be applied prior to processing the data sets with stacking and migration algorithms. The former procedure, in turn, requires detailed (few centimeter) topographic data be collected at the survey site. Since environmental surveys entail spatial resolutions on the order of one meter, the survey rate for the seismic methods is generally less than one acre per day. Finally, algorithmic processing of seismic data is sophisticated, intensive, and highly consumptive of computer resources.

Availability / Cost:

Seismic equipment is available from several manufacturers in Canada, the U.S., Japan, and Europe. The seismic gear can also be leased from local rental houses. Owing to its complexity, seismic data must generally be interpreted by a trained geophysicist, as well as inverted with proprietary computer algorithms. Accordingly, it is usually necessary to hire a field-oriented geophysicist specializing in seismic methods. Owing to the latter requirement, the dollar cost of a seismic survey of a one acre site using a multistatic (multiple-offset) technique is in the range of $6,000 to $8,000.

3.1.1.10 Gravitometry

Technical Concept:

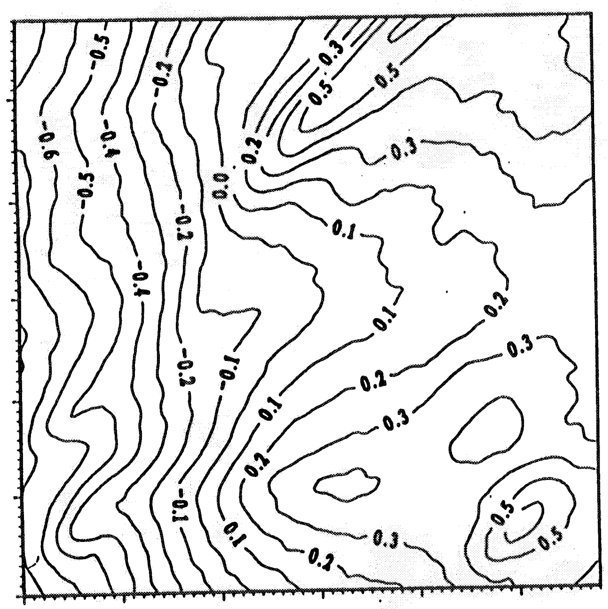
This technique, which is a passive one, detects and measures local anomalies in the earth's gravitational field. Current equipment is capable of accurately measuring both the magnitude and gradient of the local gravity field. These measures are then used to infer the size and depth of the spatial variations in physical density of the underground. In practice, geophysicists use both airborne and ground-based equipment to support their survey objectives. **Exhibit 3.1.1.10-1** and **3.1.1.10-2** present, respectively, a typical gravitometry instrument and a map obtained therewith.

GRAVITY METERS

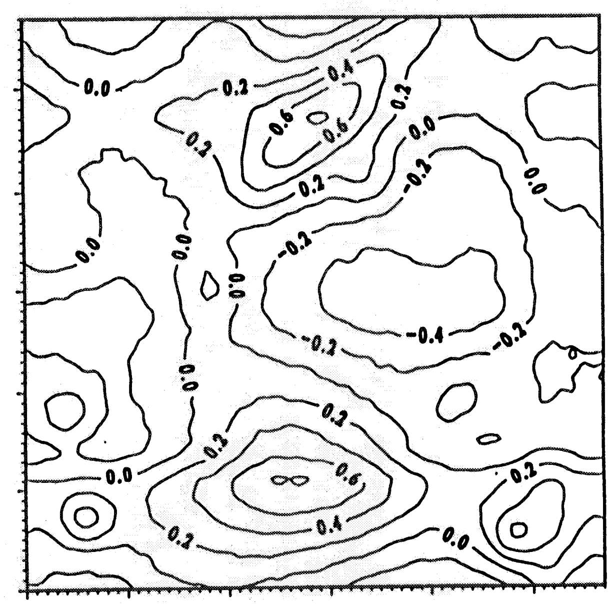
Exhibit 3.1.1.10-1: A Typical Gravitometry Instrument (CG-3 Autograv)

Exhibit 3.1.1.10-2: A Typical Map obtained utilizing a Gravitometry Instrument

Hinze Gravity and Magnetic Methods



Strike-pass filtered (N15°–75° E) gravity anomaly map (after Xinzhu and Hinze, 1983). Contour interval is 0.1 mGal. Short tick marks on margins are at 1 km intervals.



Residual gravity anomaly map after removing third-degree trend surface (after Xinzhu and Hinze, 1983). Contour interval is 0.2 mGal. Short tick marks on mar-gins are at 1 km intervals.

Geophysical Concept:

Gravitational anomalies are associated with spatial variations in the physical density of the underground. Such variations may be associated with either a natural phenomenon (*e.g.*, a cave) or a cultural event (*e.g.*, a wastesite). The ground-based surveys, which are mostly used for near-surface studies, yield data that may often be interpreted directly. The airborne surveys are more often used for deep-sounding and produce data that usually must be correlated with other geophysical information to eliminate ambiguities and maximize its geophysical value.

Geological Value:

Geophysicists use gravitometry to map and correlate density-type variations in the underground environment. Geological variations include voids (caves), dipping planes, bedrock topography, and regions with stress or fault potential. Cultural events include wastesites and archaeological zones. Although gravitometry plays a definitive role in both mineral and petroleum exploration, the technique is not often a major player in hydrogeological studies.

Deployment / Operation / Productivity:

Gravitometers are non-contact devices, which may be operated from either an airborne or a ground-based platform. In airborne surveys, the equipment is flown along flight lines orthogonal to the geological feature of interest, *e.g.* a fault line, or raster scanned for an overhead map of the survey site. Terrestrial surveys are conducted in similar fashion, but at ground levels. Productivity for the airborne modality is high (square kilometers per day), while that of the ground-based equipment tends to be much lower (less than ten acres per day). In rugged environments, it may be necessary to make topographical corrections to the collected data, which can significantly impact the rate and cost of a gravity survey.

Availability / Cost:

Ground-based gravitometers are available from a number of manufacturers in Canada, the U.S., Japan, and Europe. Owing to the sensitive nature of the equipment and need for fine static corrections, the survey task is typically left to a geophysicist trained in gravity methods. The aerial equipment is even more specialized, as well as entails careful planning and execution of flight profiles. Again, one typically hires a survey company with a gravitometer permanently installed in fixed-wing aircraft or a helicopter flight package. Costs for a one-meter ground-based survey typically run $1,500 per acre; airborne surveys are less expensive at $100 per acre, but have lower spatial resolutions (10 meters) and higher minimums ($10,000).

3.1.1.11 Neutron Imaging

Technical Concept:

This survey technique illuminates a survey site with a collimated, on-site generated beam of high energy neutrons (10s of MeVs). Neutrons are generated by use of a small portable charged particle accelerator. The surface and buried materials with substantial neutron capture or absorption cross sections at the energies in question can be expected to capture the incoming neutrons, absorb them momentarily, and then release them as neutrons of different energy, and / or result in the generation of gamma rays of characteristic energy, etc. The characteristic energy of gamma emissions monitored by an appropriate detector provide a measure of the elemental composition of contaminants at the site. With appropriate instrumentation and analytical algorithms, both neutron and gamma emissions can be used to image subsurface and chemical distribution.

Geophysical Concept:

The nuclear products resulting from the interaction of the incident neutron and the elemental species can provide a unique indication of the elemental make up of the illuminated sample. In a field operation, a collimated neutron beam would be aimed at the surface of the ground and the backscattered and emitted products sensed with an array of appropriate detectors. In another rendition, the neutron source, which is very small, can be put below the surface using a cone penetrometer or in existing wells on the site and neutron imaging with depth can be accomplished. **Exhibits 3.1.1.11-1** and **3.1.1.11-2** show, respectively, the sub-surface and surface neutron imaging schemes.

Geological Value:

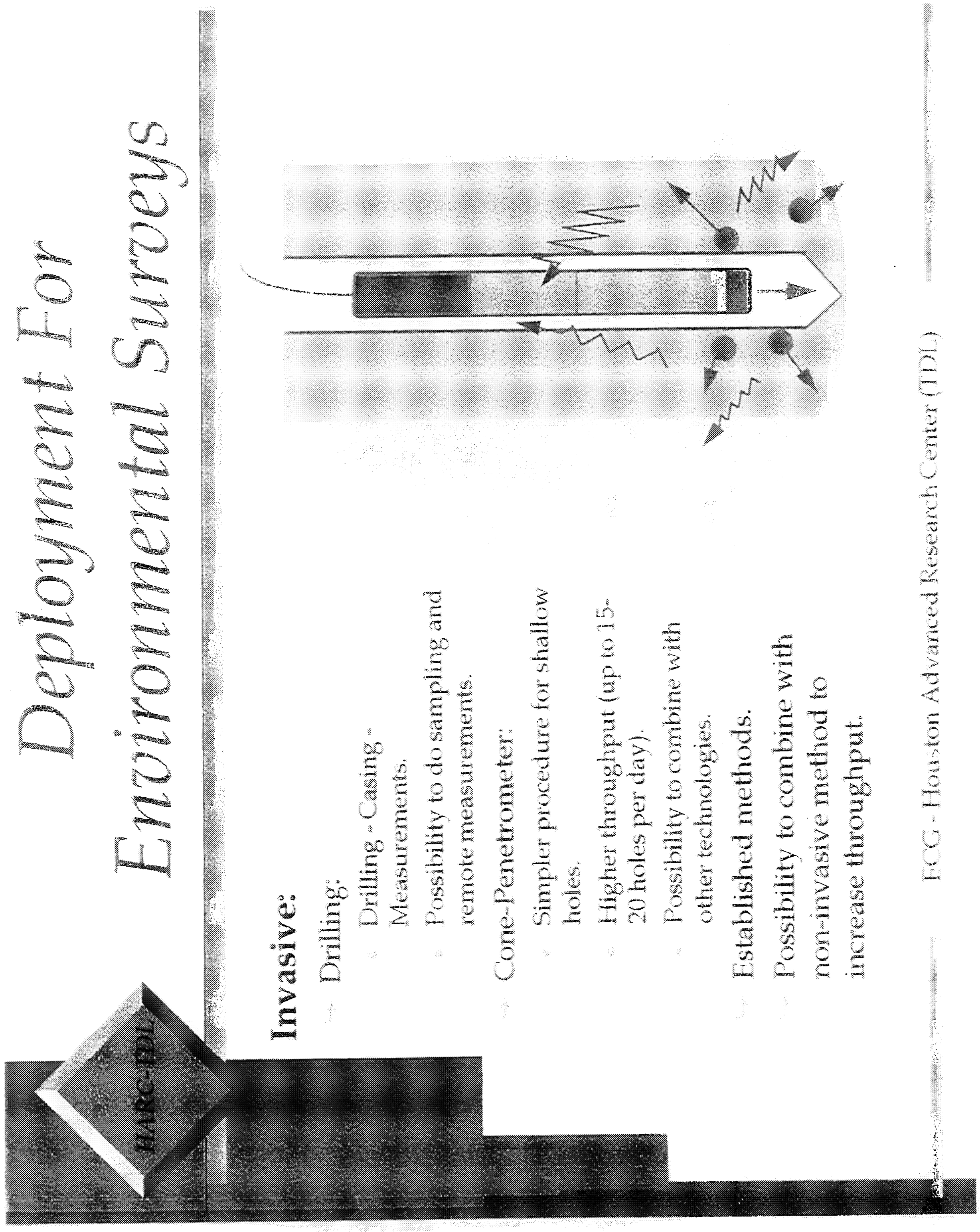
This technique can provide geophysicists with a field tool for detecting and imaging contaminant levels at and below the surface in a relatively short time (30 min. to 1 hour). The technique samples contaminants, not merely at the point of the incident neutrons, but in a substantial volume (a sphere of about 2 m). Compared with the traditional methods (field sampling followed by laboratory analysis), this technique provides information with the soil volume in-situ.

Deployment / Operation / Productivity:

As currently envisioned, this method could best be used at the designated "hot spot" as a system mounted on a truck or wheeled trailor to scan contaminants in the near-surface. As a multistatic imaging system, productivity of this technique would compare to that of other multistatic modalities (seismics, resistivity, GPR), *i.e.*, 0.2 to 0.5 acres / day.

Availability / Cost:

The technique is well founded in technology and engineering principles. Small fieldable neutron generation systems exist. Neutron imaging of chemicals, contaminants, in medicine, and for non-destructive testing has been performed using both stable neutron sources (Californium 254) as well as with small accelerator-based sources. Two DoE facilities that have some experience in this method are Idaho National Engineering Laboratory, and the Hanford Laboratory. Hardware has been developed and is in use at the Houston Advanced Research Center (HARC); its adaptation to a cone penetrometer is underway. The system would be available for use at the CTS at the MSFC for on-site confirmation of chemical contaminants. As a multistatic technique, its cost-effectiveness can be expected to approximate that of the other multistatic modalities, *e.g.*, \$2,000 to \$5,000 per acre, an estimate that will need to be re-evaluated as a part of the Phase II of this effort.



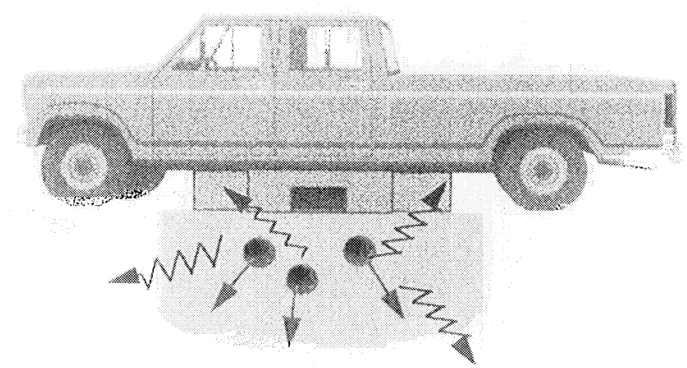
Exhibits 3.1.1.11-1: Deployment for Environmental Surveys Subsurface Mode

HARC-TDL

Deployment For Environmental Surveys (2)

Non-Invasive:

- Surface measurements
  - Probes only the top part of the formation.
  - Significantly higher throughput.
  - No concerns about site integrity.
- Use as a general survey to identity areas of concern.
- The efficiency of this technique will depend upon the chemical trace amounts in the upper subsurface.
- The possibility to use surface measurements will be tested in phase II.



ECG - Houston Advanced Research Center (TDL)

Exhibits 3.1.1.11-2: Deployment for Environmental Surveys Surface Mode

3.1.1.12 Photo-Acoustic Activation

Technical Concept:

This technique utilizes a pulsed laser beam directed at the vapor, gas, or a surface material in equilibrium with its surroundings and having an absorption band at the illumination frequency. When the beam is turned on, the energy is absorbed; when the beam is switched off, a characteristic acoustic signature is produced. This signature can be detected up to 1,000s meters away with appropriate microphone instrumentation. The technique has been demonstrated in the laboratory and is amenable for use with airborne as well as ground-based platforms. In the stand-off mode, *e.g.*, the remote operation, the laser light is aimed with telescopic optics at the distant target (10- 1,000m) and the returning acoustic pulse captured with a parabolic reflector not unlike those used by sports reporters, intelligence agents, and private investigators. The technique is capable of detecting trace amounts of chemical molecules in parts per billion. A schematic of the PADAR System is shown in **Exhibit 3.1.1.12-1.**

Geophysical Concept:

The acoustic response provides a unique indication of the chemical make-up of the illuminated sample. In geophysical applications, the wavelength of the laser pulse is stepped through a frequency set corresponding to the contaminants of interest. The magnitude and frequency of the acoustic signature is used to estimate the type and concentration of the trace chemical. It will be necessary to characterize the optical absorption bands for chemicals of interest to the NASA MSFC to identify the type of tunable laser required. The technique can also be applied in the subsurface regions when used in conjunction with fiber optics and cone penetrometers. In this sense, the method is familiarly related to the use of fiber optic sensors for detection of chemicals downhole with the cone penetrometers under the sponsorship of the EPA.

Geologic Value:

This approach can provide geophysicists with a tool for rapidly detecting and monitoring contaminants to the ppb levels. Compared with traditional methods (field sampling followed by laboratory analysis), the PADAR System would be rugged, rapid, and economical for certain contaminants even to very low concentrations.

Deployment / Operation / Productivity:

As currently envisioned the technique can be used on a wheeled cart platform to scan for above-surface contaminants, downhole in conjunction with penetrometers or can be used on an airborne platform such as a helicopter. As a monostatic device with high speed capability, the productivity can be expected to match or exceed those for other monostatic modalities, *i.e.*, 3 to 10 acres / day.

Availability / Cost:

A fully fieldable system needs some development. The equipment required is simple and readily available since laboratory facilities already exist. The tests of fiber optic based sensors downhole with cone penetrometers have already been made by the EPA. Thus, the methodology can be expected to be fully available within a few months after if has been demonstrated for "chemicals of concern" in the field. As an airborne system or ground-mobile system, its cost can be expected to be very low ($100 to $500 per acre).

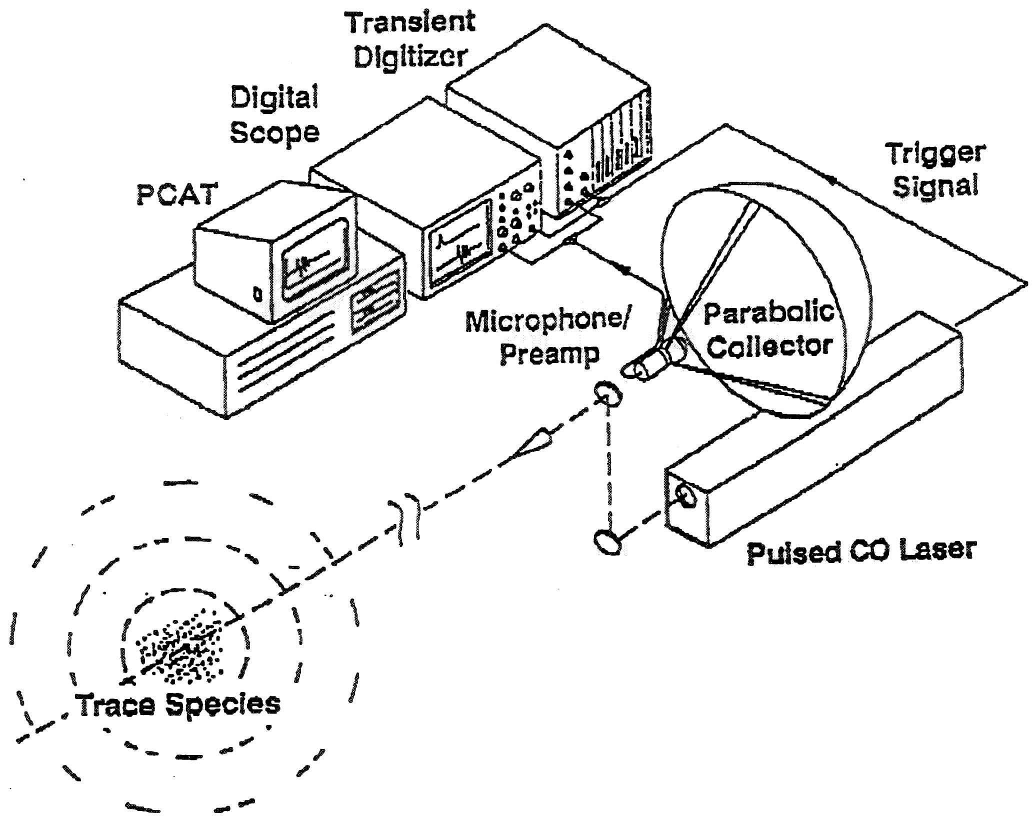


Exhibit 3.1.1.12-1: A Schematic of the PADAR System

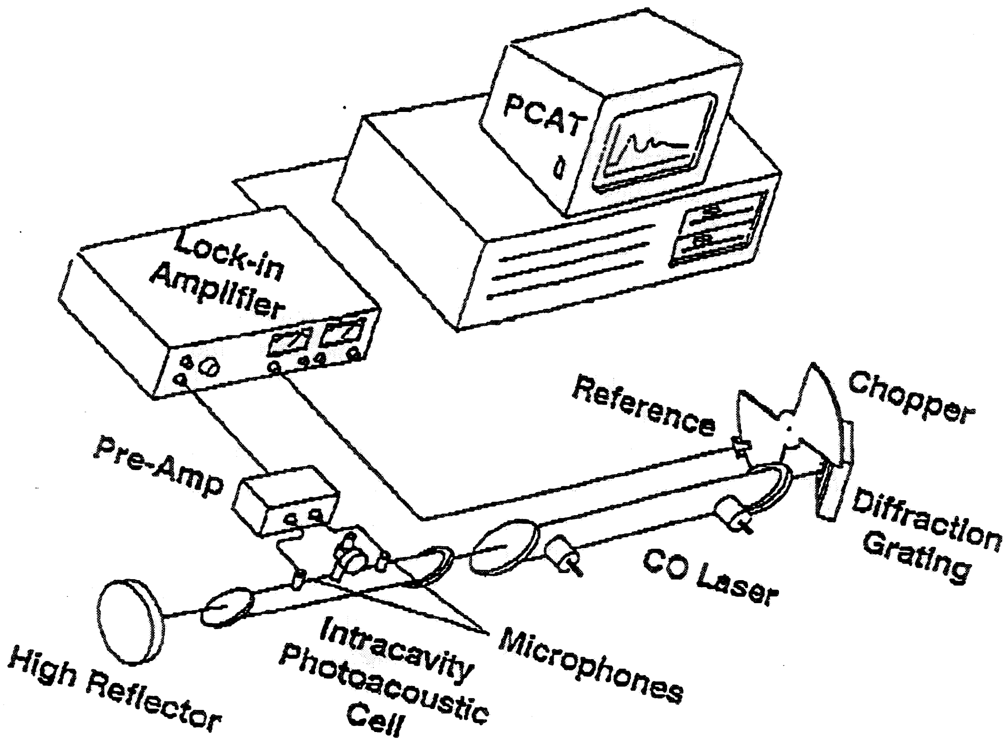


Exhibit 3.1.1.12-2: A Schematic of the Photo Acoustic Detection and Spectroscopy System

3.1.2 Sensor Selections

The criteria for selection of one or more integrated geophysical mapping sensors are based on the MSFC requirements that include technical performance effectiveness (*e.g.*, satisfy the measures of success defined), and be operationally non-invasive, practical, productive, and cost-effective. The technical effectivity includes adequate resolution of subsurface features in and up to the karst formation for assessing chemical contaminant transport and plumes to enable engineering and implementation of cost-effective remediation actions. Operationally, the systems must be usable in generally flat, swampy or wooded environment as well as enable mapping of the subsurface underlying the MSFC buildings and structures. Moreover, the selected sensors must be compatible with the applicable codes, and regulations (legal, environmental, security, etc.). Finally, sensors in the selected suite need to provide complementary rather than overlapping information. For comparative assessment of sensors, it also appears not only meaningful to use as a reference or benchmark the traditional approach of drilling of wells and analysis of borehole samples for characterizing the underground, but also to contrast the two most popular methods for mapping the geological and hydrogeological features of a survey site: seismic, and electromagnetics (magnetometry, electrical, EM, GPR sensors).

3.1.2.1 Well Drilling And Borehole Analysis

Boreholes provide the most direct and least ambiguous evidence of the geological structure of the underground at the drill point. In practice, the spatial density of boreholes and hence the dollar cost of a borehole investigation can reach staggering proportions. For example, Lawrence Livermore National Laboratory (LLNL) recently surveyed a one-square-mile (640 acres) site using the borehole technique. In all, 1,627 holes were drilled on a regular grid at $70,000 per hole, for a total cost of $114 million. Environmental boring is approximately ten-fold more expensive than conventional drilling, because steps must be taken to: *(1)* prevent inter-layer leakage; *(2)* capture and dispose of drilling spoils (both soil and water); and *(3)* deal with the more arduous permitting process. This cost should be compared with that associated with an airborne EM survey at $100,000 to $250,000 or conventional ground-based GPR survey at $0.6M to $1.5M for a square-mile zone. The cost obviously depends on survey grid, resolution of features and precision required of a survey. The grid spacing used at the LLNL site was about 30 meters, which is considered very coarse for environmental surveys that typically involve wastesite geometries and contaminant plumes with much finer (one-meter) scales.

3.1.2.2 Seismic / Electromagnetic

In subsurface geophysics, both conceptual and operational similarities exist between seismic reflection and GPRs. The seismic and the multistatic GPR use related inversion algorithms. Both methods use reflections of energy from underground features, such as rocks and interfaces. In particular, the seismic methods are most sensitive to the mechanical properties of earth materials and relatively insensitive to the chemical make-up of both the earth materials and the interstitial fluids. The seismic energy can easily penetrate damp clays and briny waters. The radar normally works best in the absence of electrically conducting materials near the earth's surface. The radar energy readily passes through unconsolidated dry sands, while high-frequency seismic waves are poorly transmitted by such materials.

Seismic and GPR methods have substantially less similarities with the electrical resistivity and polarization methods. Electrical methods, by contrast, are sensitive to the contained fluids and the presence of magnetic and electrically conductive materials. In other words, the measurable physical parameters upon which the seismic method depends are quite different from the physical parameters measured in the electromagnetic methods. Clearly, different methods provide different information and with substantial differences in their performance characteristics. Thus, a survey of any given site can and will generally require several sensor modalities to yield the totality of data required. The selected modalities must also be compatible with respect to operational logistics and affordability.

3.1.2.3 Comparative Assessment Matrix

Numerous sensor systems can potentially meet one or more of these constraints. They are compared in terms of the criteria and requirements set above and the results are provided in **Exhibits 3.1.2.3-1a.b.c** and **d**, and **3.1.2.3-2a, b, c** and **d**, respectively, showing operational and geophysical characteristics of the various terrestrial modalities.

Characteristic	Sensor		
	Magnetometry	Gravitometry	Resistivity
Sensed Quantity	Magnetic Field and Gradient	Gravity Field and Gradient	Resistivity and SP
Invasiveness	None	None	Little
Spatial Resolution	Moderate	Moderate	Moderate
Exploration Depth	High	High	Moderate
Noise Interference	Moderate	Moderate	Moderate
Cultural Interference	High	Low	High
Operational Complexity	Low	Moderate	High
Productivity	High	High	Very Low
Processing Load	Low	Low	High
Ease of Interpretation	Moderate	Easy	Moderate
Technical Maturity	Mature	Mature	Moderate
Site Restrictions	No powerlines or fences	Geologic diversity	Not effective in dry soils
Advantages	Metal Detection	Mapping Voids	Mapping Karst
Disadvantages	Geologic Insensitivity	Equipment Complexity	Labor Intensive
Equipment cost	Modest	High	Modest
Survey Cost	Low	Moderate	Very High

Exhibit 3.1.2.3-1a: Operational Characteristics of Terrestrial Sensors

Characteristic	Sensor		
	TDEM (Slingram)	FDEM	VLF
Sensed Quantity	Vertical Resistivity	Horizontal Resistivity	Near-Surface Resistivity
Invasiveness	None	None	None
Spatial Resolution	Moderate	Moderate	Moderate
Exploration Depth	3 - 100 m	3 - 50 m	3 - 50 m
Noise Interference	Moderate	Moderate	Moderate
Cultural Interference	High	Low	High
Operational Complexity	Moderate	Moderate	Low
Productivity	High	High	High
Processing Load	Modest	Low	Modest
Ease of Interpretation	Moderate	Easy	Moderate
Technical Maturity	Mature	Mature	Mature
Site Restrictions	Walkable	Walkable	Walkable
Advantages	Good Depth Resolution	Ease of Use	No Transmitter
Disadvantages	Noise Sensitivity	Poor depth Resolution	Transmitter Reliability
Equipment Cost	Moderate	Low	Low
Survey Cost	Low	Low	Low

Exhibit 3.1.2.3-1b: Operational Characteristics of Terrestrial Sensors

Characteristic	Sensor		
	Seismics (Reflect/Refract)	Mono-GPR and UNP	Multistatic GPR
Sensed Quantity	Acoustic Impedance Contrasts	Electrical Impedance Contrasts	Electrical Impedance Contrasts
Invasiveness	Spikes	None	None
Spatial Resolution	Moderate	High	High
Exploration Depth	5 - 500 m	Variable	Variable
Noise Interference	Low	Moderate	Low
Cultural Interference	Moderate	Moderate	High
Operational Complexity	High	Low	High
Productivity	Low	High	Moderate / High
Processing Load	High	Low	Moderate
Ease of Interpretation	Moderate	Easy	Moderate
Technical Maturity	Mature	Mature	Mature
Site Restrictions	Implantable Electrodes	No conductive Soils	No conductive Soils
Advantages	Depth of Penetration	High Resolutions	High Resolutions
Disadvantages	Labor Intensive	Ground Clutter	Labor Intensive
Equipment cost	Modest	Modest	Modest
Survey Cost	High	Low	Low

Exhibit 3.1.2.3-1c: Operational Characteristics of Terrestrial Sensors

Characteristic	Sensor		
	Neutron Activation	Monostatic VETEM	Photo-Activation
Sensed Quantity	Atomic Chemistry	Impedance Contrast	Molecular Chemistry
Invasiveness	Variable	None	None
Spatial Resolution	Moderate	High	Very High
Exploration Depth	2 - 3 m	3 - 10 m	Surface
Noise Interference	Very Low	Moderate	Low
Cultural Interference	Low	Moderate	Low
Operational Complexity	Moderate	Moderate	Low
Productivity	Moderate	High	Moderate
Processing Load	Moderate	High	Low
Ease of Interpretation	Moderate	Easy	Moderate
Technical Maturity	Basically Mature	Quasi-mature	Laboratory
Site Restrictions	Surface Access	Surface Access	Surface Access
Advantages	Atomic Specificity	Extra Depth Penetration	Chemical Specificity
Disadvantages	Variable Penetration	Variable Penetration	Poor depth Penetration
Equipment cost	Moderate	Moderate	Moderate
Survey Cost	Moderate	Moderate	Moderate

Exhibit 3.1.2.3-1d: Operational Characteristics of Terrestrial Sensors

Characteristic	Geophysical Sensor		
	Magnetometry	Gravitometry	Resistivity
Sensed Quantity	Magnetic Field and Gradient	Gravity Field and Gradient	Resistivity and SP
Depth Resolution	Fair	Good	High
Lateral Resolution	Good	Good	Good
Profile Capability	Partial	Yes	Yes
Plan View Capability	Yes	Yes	Yes
Best Soil Conditions	Non-Magnetic	Variable	Wet / Conductive
Worst Soil Conditions	Magnetic	Variable	Dry / Resistive
Impact of Surface Roughness	Moderate	Moderate	Moderate
Impact of Brush and Woods	Moderate	Moderate	Moderate
Suitability for Plumes	Low	Low	High
Suitability for Karst	Low	Moderate	High
Ground Water (alluvial)	Low	Low	High
Ground Water (consolidated)	Low	Moderate	High
Ground Water (hard rock)	Low	Moderate	High
Ground Water (moving)	Low	Low	Moderate
Solid Waste Sites	High	High	High
Metal Pipes/Drums	High	Moderate	Moderate
Caves/Voids	Low	High	High
Faults/Fractures/Planes	Low	Moderate	High
Liquid Waste Sites	Low	Low	High
Contaminant Plumes	Low	Low	High
Military Sites	High	Moderate	Moderate
Archaeological Sites	High	Moderate	Moderate

Exhibit 3.1.2.3-2a: Geophysical Characteristics of Terrestrial Sensors

Characteristic	Geophysical Sensor		
	TDEM (Slingram)	FDEM	VLF
Sensed Quantity	Vertical Resistivity	Horizontal Resistivity	Near-Surface Resistivity
Depth Resolution	Fair	Fair	Fair
Lateral Resolution	Good	Fair	Fair
Profile Capability	Yes	Yes	Yes
Plan View Capability	Yes	Yes	Yes
Best Soil Conditions	Non-Magnetic	Moist or Wet	Dry / Resistive
Worst Soil Conditions	Magnetic	Dry / Resistive	Wet Clay
Impact of Surface Roughness	Moderate	Moderate	High
Impact of Brush and Woods	Moderate	Moderate	High
Suitability for Plumes	Low	High	High
Suitability for Karst	Moderate	High	High
Ground Water (alluvial)	Low	High	High
Ground Water (consolidated)	Low	High	HIGH
Ground Water (hard rock)	Low	High	High
Ground Water (moving)	Low	Low	Low
Solid Waste Sites	High	High	High
Metal Pipes/Drums	Very High	Moderate	High
Liquid Waste Sites	Low	Moderate	High
Contaminant Plumes	Low	High	High
Caves/Voids	Low	High	High
Faults/Fractures/Planes	Low	high	High
Military Sites	High	Moderate	High
Archaeological Sites	High	Moderate	Moderate

Exhibit 3.1.2.3-2b: Geophysical Characteristics of Terrestrial Sensors

Characteristic	Geophysical Sensor		
	Seismics (Reflect/Refract)	**Mono-GPR and USP**	**Multistatic GPR and USP**
Sensed Quantity	Acoustic Impedance Contrasts	Electrical Impedance Contrasts	Electrical Impedance Contrasts
Depth Resolution	Fair	Exceptional	Exceptional
Lateral Resolution	Good	Exceptional	Exceptional
Profile Capability	Yes	Yes	Yes
Plan View Capability	Yes	Yes	Yes
Best Soil Conditions	Layered and Uncluttered	Dry and Resistive	Dry and Resistive
Worst Soil Conditions	Unlayered	Wet Clay	Wet Clay
Impact of Surface Roughness	Moderate	Moderate	Moderate
Impact of Brush and Woods	Moderate	Low	Moderate
Suitability for Plumes	Low	Moderate	High
Suitability for Karst	Moderate	High	High
Ground Water (alluvial)	Low	Moderate	Moderate
Ground Water (consolidated)	Moderate	Moderate	Moderate
Ground Water (hard rock)	High	Very High	Very High
Ground Water (moving	Low	Low	Low
Solid Waste Sites	Low	High	High
Metal Pipes/Drums	Low	High	High
Liquid Waste Sites	Low	Moderate	High
Contaminant Plumes	Low	Moderate	High
Caves/Voids	Low	Very High	Very High
Faults/Fractures/Planes	Low	Very high	Very High
Military Sites	High	Moderate	High
Archaeological Sites	High	High	High

Exhibit 3.1.2.3-2c: Geophysical Characteristics of Terrestrial Sensors

Characteristic	Geophysical Sensor		
	Neutron Activation	**Monostatic VETEM**	**Photo-Activation**
Sensed Quantity	Atomic Chemistry	Impedance Contrast	Molecular Chemistry
Depth Resolution	Fair	Good	Exceptional
Lateral Resolution	Good	Good	Exceptional
Profile Capability	Partial	Yes	Yes
Plan View Capability	Yes	Yes	Yes
Best Soil Conditions	Variable	Dry / Resistive	N/A
Worst Soil Conditions	Variable	Conductive	N/A
Impact of Surface Roughness	Low	Moderate	Low
Impact of Brush and Woods	Moderate	Moderate	Low
Suitability for Plumes	High	High	Moderate
Suitability for Karst	Moderate	Moderate	Low
Ground Water (alluvial)	Variable	High	High
Ground Water (consolidated)	Variable	Moderate	Variable
Ground Water (hard rock)	Variable	Low	Variable
Ground Water (moving)	Variable	Low	Variable
Solid Waste Sites	Moderate	High	Variable
Metal Pipes/Drums	Moderate	Moderate	Low
Liquid Waste Sites	Variable	High	Variable
Contaminant Plumes	High	High	High
Caves/Voids	Low	Moderate	Low
Faults/Fractures/Planes	Low	Moderate	Low
Military Sites	Moderate	Moderate	Low
Archaeological Sites	Moderate	Moderate	Low

Exhibit 3.1.2.3-2d: Geophysical Characteristics of Terrestrial Sensors

3.1.2.4 Survey Relevance To CTS

Exhibits 3.1.2-4-1a, b and **c** show the relevance of survey modalities to the CTS in terms of the capability to meet measures of success. The applicability of each modality at the CTS is indicated with a two-level scale: appropriate (A), and not appropriate (NA).

Measure of Success	Geophysical Sensors		
	Magnetometry	Gravitometry	Resistivity
Intact Bedrock	NA	A	A
Permeable Zones	A	NA	A
Solid Wastes	A	A	A
Contaminant Plumes	NA	A	A
Military Artifacts	A	NA	A
Archaeological Artifacts	A	NA	NA

Exhibit 3.1.2.4-1a: Contribution to Measures of Success

Measure of Success	Geophysical Sensors		
	TDEM	FDEM	VLF
Intact Bedrock	A	A	A
Permeable Zones	A	A	A
Solid Wastes	A	A	A
Contaminant Plumes	A	A	A
Military Artifacts	A	A	A
Archaeological Artifacts	A	A	A

Exhibit 3.1.2.4-1b: Contribution to Measures of Success

Measure of Success	Geophysical Sensors		
	Seismic	GPR	VETEM
Intact Bedrock	A	A	A
Permeable Zones	A	A	A
Solid Wastes	A	A	A
Contaminant Plumes	A	A	A
Military Artifacts	A	A	A
Archaeological Artifacts	A	A	A

Exhibit 3.1.2.4-1c: Contribution to Measures of Success

In these exhibits neutron imaging and photo-activation techniques are not included since their primary objectives are to map chemical contaminants in the field. With these technologies no subsequent laboratory chemical analysis is necessary. For their intended objectives, these techniques are directly relevant to such measures of success as solid waste, contaminant plumes, permeable zones, military artifacts, and trace chemicals in man-made artifacts.

3.1.2.5 Technical Overlap Within Modalities

Some geophysical techniques use similar energy sources and thus tend to overlap one another in the broad sense that the two different modalities will measure (or effectively measure) the same geophysical quantity. However, their performance such as resolution, sensitivity and depth of penetration can differ sufficiently as to provide complementary and useful results. For example, reflection and refraction seismics represent two different approaches to estimating the propagation velocity of seismic vibrations in a layered earth. Likewise, EM, VLF, and magnetotellurics attempt to map the conductivity and dielectric properties of the survey site with electromagnetic radiation, but each uses a different survey configuration and provide different information. Below, we have attempted to rank order various survey techniques relative to their capability for meeting each measure of success per the NASA MSFC requirements. These rankings provide broad guidance for selection of sensor suites consistent with the goals of a specific site survey. This ranking should not be regarded as absolute because a large number of variables affect each modality. **Exhibit 3.1.2.5-1** presents our ranking of the three appropriate modalities in each case. In this ranking the first choice is the most appropriate followed by the second and third choices.

	Geophysical Sensor		
Measure of Success	**First**	**Second**	**Third**
Intact Bedrock	Seismic	Resistivity	TDEM
Permeable Zones	Resistivity	GPR	Seismic
Solid Wastes	TDEM	GPR	FDEM
Contaminant Plumes	GPR	Resistivity	VETEM
Military Artifacts	GPR	Magnetometry	TDEM
Archaeological Artifacts	GPR	Magnetometry	TDEM
Contaminants / Surface and Near-surface Imaging	Neutron Activation	Optical Activation	Well sampling and Analysis

Exhibit 3.1.2.5-1: Best Modalities for Each Measure of Success

The differences between the first and second choices are indicative of considerations pertaining to productivity, penetration, and resolution, etc. For example, GPR at low center frequencies and improved processing methods could provide data for intact bedrock structure, permeable zones, and solid waste that is good or better than the first choice modalities shown above. Such issues can only be settled with data collected at the CTS with several sensor modalities of choice.

3.1.2.6 Operational Considerations

As with any survey site, the CTS presents its own set of operational issues, constraints, and restrictions. We discuss these below.

Permits And Licenses:

The proposed survey modalities are all essentially non-invasive and entail no hazardous aspects. Nonetheless, a number of Federal, State, and Local permits may be required prior to undertaking a geophysical survey of the CTS. Some examples of potential permits and license requirements include: airborne surveys which may require local and / or FAA approvals; Hazardous Waste permits for ground-based surveys of the Heavy Metal Waste Disposal area at the corner of Martin Road and Tiros Street; and a license and a permit for transport, staging and use of equipment capable of producing nuclear radiations (neutrons, gammas, charged particles) for on-site neutron imaging. HARC already has the license for the transport and use of the accelerator-based on-site neutron generation source. Specific permit and license requirements are being evaluated. At this time, discussions with the ADEM, and the Safety and Health Office as well as the Environmental Directorate at the MSFC indicate no permit or license requirement for a survey of the site with various sensor modalities except that these departments will like to be kept informed of the activities we perform under the survey. However, if for some reason a requirement for any license or permit emerges, they will have to be obtained early in Phase II of the project.

Environmental Constraints:

Major portions of the CTS are heavily wooded and thick with undergrowth. In addition, streams, sinkholes, artesian wells, and buildings dot the wooded sites. In such an environment it could be difficult to execute straight and level survey lines in parts of the CTS, unless aided with differential GPS. Specifically, the wheeled survey devices may prove difficult to operate in such environments. The portable survey devices (*e.g.*, FDEM and TDEM) may also prove challenging, but still possible in a wooded environment. The ground-contact modalities (*e.g.*, resistivity, seismic, GPR) are less impacted by the more rugged environment, since static (vertical and lateral) corrections represent a normal part of the field protocols for these modalities.

Portions of the CTS have been developed for professional, recreational, and ancillary use. These include assembly buildings, a public park, and paved parking lots. In addition, power lines, telephone lines, water lines, and sewer lines criss-cross the developed areas. The latter can play havoc with both magnetometers and the EM devices, unless steps (signal averaging) are taken to mitigate their effects. Also, the electric and seismic modalities involve implanted sensors, which are not compatible with the paved areas or on the inside floor of the buildings. The GPR and the EM techniques, by contrast, operate efficiently in such areas.

Finally, weather conditions in the Huntsville area need to be considered. The Winter season features more precipitation than the Summer one. Thus, it is prudent to run the GPR surveys, which prefer dry soils, in the dryer months; and the resistivity (and self potential) ones, which favor moist conditions, in the wetter ones.

Overflight:

Depending on survey goals and site factors, airborne surveys can be employed for either or both a detailed survey and screening of the site to detect and delineate environmental AOCs and relatively smaller "hot spots" that can be subjected to more detailed investigations using appropriate ground-based sensors. Airborne surveys can be helicopter or aircraft based. There is an air flight path restricted zone over the CTS. Thus, coordination of survey flights with Redstone Arsenal and the MSFC will be required for airborne surveys. At this time, the indications are that the intended survey site will not likely be required to be evacuated of both the government and civilian personnel for aircraft surveys with low power EM and RF sources.

The FAA regulations for low-altitude airborne surveys of the CTS need to be further examined. We understand that government personnel (and their families) work, exercise, and recreate on and near the CTS. In the event FAA regulations indicate any requirement for evacuation of the Sste for an airborne survey, either the arrangements will have to be made to clear the survey site to FAA standards, or the airborne surveys could be conducted in a short few hours over a weekend, or the helicopter-based surveys would be used on a restricted portion of the CTS. A similar situation was encountered at the significantly more populated sites at Oak Ridge National Laboratory (ORNL) when that site was surveyed by helicopter in 1993.

For a survey of the entire MSFC site (some 1,800 acres) and / or the larger Redstone Arsenal, use of terrestrial survey systems alone may not be feasible for financial and logistical reasons. Like ORNL, much of the acreage at the MSFC and Redstone Arsenal is devoid of buildings and people, so an aerial survey becomes even more feasible and desirable, both for logistical and cost-effectiveness considerations.

3.1.3 Selected Sensors (Preliminary)

Based on the information discussed above, it is clear that several survey modalities would be required to meet the overall mission of the MSFC. As an initial selection, we recommend the following ground-based and airborne sensors for use at the CTS. Without the additional site data and detailed analyses, further refinement in the selection of sensors from the initial list will not be gainful. **Exhibit 3.1.3-1** and **Exhibit 3.1.3-2** provide a list of the leading suppliers of the selected terrestrial and airborne survey systems, respectively. From results obtained at the CTS, it would be possible to refine the choice of survey systems for use at the larger MSFC and Redstone Arsenal sites, and similar sites elsewhere.

Equipment Type	Leading Suppliers		
	First Choice	Alternate	Back-Up
Resistivity	Advanced Geo.	Oyo	Phoenix
Magnetometry	Geonics	Geometrics	Zonge
FDEM	Geonics	Oyo	Zonge
TDEM	Geonics	Zonge	Oyo
Tellurics	Geometrics	N/A	N/A
Monostatic GPR	GeoRadar	Sensors & Software	Mitsui / GSSI
Multistatic GPR	HARC	Sensors & Software	N/A
Seismics	Geometrics	Oyo	-
VETEM	USGS (Boulder)	N/A	N/A
Neutron Imaging	HARC	N/A	N/A

Exhibit 3.1.3-1: Leading Suppliers of Terrestrial Geophysical Gear

Equipment Type	Leading Suppliers		
	First Choice	Alternate	Back-up
EM/Magnetometry	Aerodat	Dighem	Scintrex
Helicopter GPR	AES	SRI	Battelle
Aerial Photography	AES	Generic	N/A
Satellite Imagery	NASA	Spin-2	France

Exhibit 3.1.3-2: Leading Suppliers of Airborne Geophysical Services

3.1.4 Preliminary Survey System Concepts

Multiple sensor systems with both ground-based and airborne modalities are selected for the CTS survey. This is due to the fact that they can provide complementary data cost effectively.

3.1.4.1 Ground Sensors

Resistivity / SP:

We selected the resistivity technique for use at the CTS, because of its capability for 2D and 3D imaging of karsted environments, such as exists throughout the MSFC and Redstone Arsenal. This modality should provide important clues about bedrock condition, zones of high permeability, water tables, and cavities (air and water-filled). In addition, we included the SP method since the technique comes as a "bonus" with the resistivity technique. The latter has special capability for detecting moving water, which also exists at the MSFC and Redstone Arsenal. Owing to the multifold (multistatic) nature of this modality and manual effort required to insert electrodes, it may be used at selected portions of the CTS.

Magnetometry:

We elected to use a time-gated metal detector, such as manufactured by Geonics (EM61) because of its ability to detect metal targets, such as 55-gallon drums, copper wire, sewer lines, and re-bar. The latter equipment, which technically is classified as a TDEM instrument, is capable of detecting metal conductors of all types with high spatial precisions. Alternatively, the MagMapper from Geometrics could be used for this assignment. The MagMapper features somewhat better depth penetration, but poorer depth and lateral resolutions. It is also insensitive to non-ferrous metals.

FDEM:

FDEM was selected to provide plan-views of the apparent resistivity of the CTS. In particular, we envision using two instruments manufactured by Geonics, which are based on the same geophysical mechanism, but optimized for different depths. The first version (EM31) is a portable unit for very-near-surface (5 - 6 m) studies. The second version (EM34), also portable, is operated for somewhat deeper surveys (50 - 60 m).

TDEM / Magnetotellurics:

It is anticipated that resistivity cross sections will be needed at critical regions of the CTS. Two options are available. Geonics TDEM and Geometrics magnetotellurics. With the Geonics equipment (Protem), the TDEM survey is conducted in the Slingram mode with two horizontally displaced co-planar vertical loops that are optimized for accurate vertical profiling of near-surface environments. It offers high speed and can produce 3D maps of sections of the CTS despite its rugged features..

With the Geometrics equipment (Stratagem), the magnetotellurics survey is conducted with ground-contact loops and dipoles. It is capable of mapping deeper ground-water environments than the Geonics gear. It too can produce 3D resistivity maps of the site. However, because magnetotellurics is a quasi-multistatic technique, it will be less expensive to restrict its use to occasional survey lines and selected portions of the CTS.

GPRs:

Two versions of the GPR are selected for use at the CTS: monostatic GPR and multistatic GPR. Monostatic GPR provides portability and capability for geological and hydrogeological characterization as well as detection / imaging of cultural and military artifacts, particularly in the dry seasons at the MSFC. The technique is considered for use to provide 3D maps of large portions of the CTS.

Likewise, we selected multistatic GPR for its demonstrated capability for making high-resolution images of complex (cluttered) underground environments, including wastesites, cultural objects, and contaminant plumes. Owing to the multistatic character of the latter technique, its use is necessarily restricted to occasional survey lines and selected regions of the CTS.

Seismic:

We selected the seismic mode for its traditional capability for identifying and mapping layered environments, including intact bedrock, fractures, and faults. We recommend that both the reflection / refraction interpretations be applied to the collected data. Owing to the multistatic nature of this modality, its use will be restricted to selected areas of the CTS.

VETEM:

We selected VETEM for its potential for surveying very-near-surface wastesites and contaminant plumes. Like its forerunners, FDEM and TDEM, this technique is monostatic and thus can survey large portions of the CTS in a cost-effective manner. However, the use of this modality is contingent on the availability of the VETEM gear and a co-funding mechanism with DoE for its use at the CTS.

Neutron Imaging:

Use of this modality at the CTS is selected because of its unique capability to detect and map chemicals at the surface and within the near-surface (in a hemisphere of about 3 m radius under the surface). Initial use of the technique can be mapping with ground-based equipment at the surface which can then be confirmed by using the technique progressively downhole in existing wells or in conjunction with a cone penetrometer. In particular, the initial use of the method will focus on suspected "hot spots" on the site.

3.1.4.2 Overhead Sensors

Helicopter EM:

We recommend that the MSFC follow the lead of ORNL and undertake a helicopter-based survey of the CTS. Specifically, we recommend an aerial survey comprising two modalities: FDEM and magnetometry. This survey would provide an overview of the geological make-up of the MSFC and environs, as well as identify suspected (or confirm known) AOCs.

Helicopter GPR:

We selected a helicopter-borne GPR for a rapid survey of the CTS to determine a full picture of the site and what exists underneath, in particular, to discern AOCs for detailed subsequent surveys.

Aerial Photography:

We are recommending that low-altitude, high-resolution aerial photographs be taken of the CTS. In contrast to the higher-altitude imagery, the close-up photographs will provide a starting point for a meter-by-meter environmental analysis of the CTS. Moreover, these photographs will provide detailed information on both natural and cultural artifacts at the CTS. In addition, it will be useful to collect IRimagery at the same time since this information can provide important clues to soil type, surface temperature, and vegetation, waste pits, etc. For this modality, we are conducting discussions for use of an airborne system that was developed under the NASA Goddard Technology Transfer program. This project involved HARC and ECG personnel. The system is capable of providing topographic maps with as low as one-foot contours.

Satellite Imagery:

We recommend that the public archives (here and abroad) be searched for satellite imagery of the MSFC, both in the optical and radio- frequency bands. The focus would be IR, mm-wave, and microwave imagery that might help determine surface type, soil type, surface moisture, surface temperature, underground temperature, and broad but useful information on likely areas with historical changes commensurate with changes in the use pattern, and potential AOCs.

3.2 Detailed Description of Selected Technologies

This section contains in detail a description of those selected technologies that are emerging but essentially available and have relevancy to the MSFC site. They include GPR and associated recent advances, and Neutron Imaging. Other modalities selected from the existing suite of sensors are not discussed here since the summary descriptions contained in the previous section are regarded as sufficient.

3.2.1 GPRs

A relatively new technique for subsurface imaging, GPR surveys are conducted by using a GPR, either in a ground-based configuration or as an airborne system. The 2D and 3D imagery can be created with both configurations, and both can used in monostatic and multistatic modes. In a good data area, GPR can provide a crisp image of the disposition of subsurface boundaries, **Exhibit 3.2.1-1.** One of the primary advantages of the GPR method is that the resolution is unparalleled among continuous sampling methods. Using a 450 MHz antenna, an object buried at 10 feet (about 3 m) can be resolved in typical soil if it is seven inches (0.18 m) or greater in diameter. Additionally, GPR is inexpensive compared to other methods such as shallow seismic because data acquisition is easy and rapid, requiring minimal manpower.

However, there are certain disadvantages associated with the GPR method. A limitation of GPR in subsurface imaging is the variability of success in imaging because of both the transient and permanent site conditions. That is, some sites will always yield data of poorer quality than other sites. In the sense of a conventional GPR application, an area where the soil conductivity is minimal provides the most penetration. Transient conditions related to soil moisture can also affect the quality of the readings. A recent rain, especially in a clay-rich soil, can increase the attenuation of the transmitted wave so that little return signal can be recorded.

Despite the limitations, GPR has been used successfully in many applications. For example, highway departments use it to investigate the thickness and competence of the asphaltic layer (Carter et al., 1992 and Lau et al., 1992), the extent and location of cracks in rock faces (Toshioka et al., 1995), and archaeologists and criminologists map grave sites (Goodman, 1994). In the environmental area, the technique has been used to locate buried drums and the outlines of buried tanks (Nyquist and Doll, 1993), to locate the water table (Beres and Haeni, 1991, Annan and Cosway, 1991, Johnson, 1992), to map dispersing plumes within a soil volume (Daniels, et al., 1995), to map fractures within plutonic rocks (Stevens et al., 1995), and many others like contaminant plumes and military artifacts. The application of GPR to hydrogeologic studies is well-documented. In a study of the detection of Light Non-Aqueous Phase Liquid (LNAPL) dispersion, (Daniels and Grumman, 1995) note that GPR successfully detects gasoline auras based on the changes in relative permittivity. These changes are associated with the presence of the vapor phase of volatile liquids.

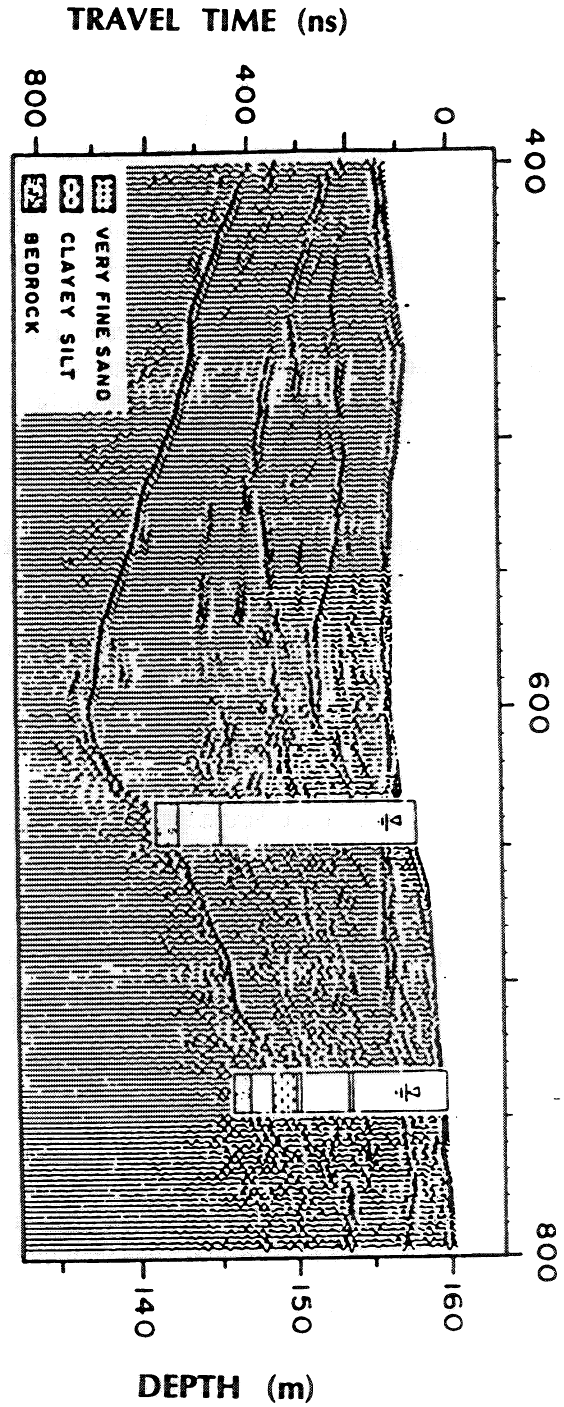


Exhibit 3.2.1-1: State-of-the-art GPR recording from an optimal site. This profile crosses clean sandstone sediments overlaying bedrock. From Davis and Annan, 1992.

The issue of whether GPR can directly image uncontained contaminants is a present research topic. Some encouraging studies show pollutants appear on GPR records quite clearly. For example, hydrocarbon contaminants have been shown to cause a blanking effect on GPR records, **Exhibits 3.2.1-2, 3.2.1-3, and 3.2.1-4**. Ulrych and Sampaio have recently utilized GPR to successfully investigate DNAPL (dense non-aqueous phase liquids) like PCE and TCE in the subsurface. Both the lateral distribution and migration with time of PCE have been clearly mapped, **Exhibits 3.2.1-5, 3.2.1-6, 3.2.1-7, and 3.2.1-8**.

In addition to the recent advances in GPR technology, described later, the technology exists as to be readily available for use at the MSFC site. Low-cost GPR acquisition systems and even contractors providing contract services are available. The ECG Team has a state-of-the-art GPR land system with 225, 450, and 900 MHz antennas and a survey wheel that is available for use.

Seismic processing of GPR data:

The oil and gas industry has invested hundreds of millions of dollars in the development of signal processing methods for use in seismic reflection profiling of oil and gas reservoirs. These methods increase the signal-to-noise ratio, increase the resolution, and remove extraneous events from seismic data to produce a cross-section of the earth. It is possible to use these methods on GPR data to realize significant improvements in image quality (Fisher et al, 1992). The Geotechnology Research Institute of the HARC / GTRI) is a leader in the development of innovative algorithms for imaging complex geologic structures on seismic reflection data. Advanced algorithms developed for imaging beneath salt deposits, faults and in other areas where complicated geology can impede normal seismic techniques are available for use on GPR data acquired at the MSFC. However, in many cases, commonly used algorithms that are less expensive to implement will provide an acceptable image quality.

Using the seismic analog for GPR involves a change in the mode of acquisition of at least some of the GPR records. In order to measure the velocity of the waves as they travel through the soil, seismologists use a CMP gather, **Exhibit 3.2.1-9.** This is a collection of source-receiver positions having a common half-way distance. As source-receiver distances are increased, the resulting increases in travel times are removed from the data, thus dramatically improving signal-to-noise ratio.

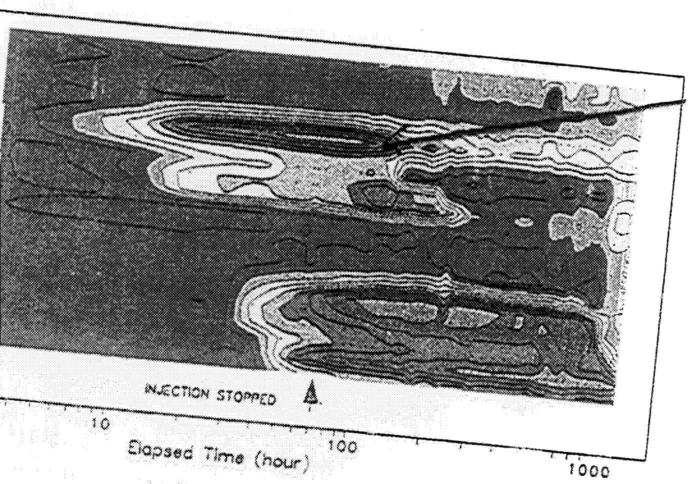
A second technique which clarifies GPR results is the use of 3D rather than 2D surveys. A 3D seismic or GPR survey can be processed to place all of the energy in the correct 3D position, removing unwanted artifacts that can lead to erroneous interpretations of 2D data. Daniels and Grumman (1995) improved visualization of hydrocarbon contamination at a gas station through the use of 3D processing, compare **Exhibits 3.2.1-3** and **3.2.1-4.** Their results indicate a blanking effect characteristic of hydrocarbon contamination.

Previous work in signal processing of GPR data at HARC / GTRI:

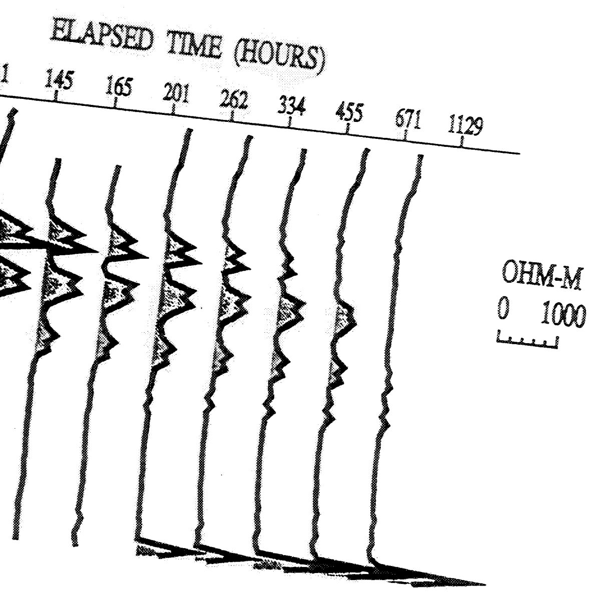
Exhibits 3.2.1-10 and **3.2.1-11** illustrate the enhancement of GPR images after signal processing, to be described later. These figures are examples of work done at GTRI under a contract with the Gas Research Institute. Further work with the Gas Research Institute is underway to provide a field-based processing unit that will process 3D surveys in real-time for the location of gas pipelines and leaks (GRI Contract # 5094-260-2963). In other work, the location of a buried trench is enhanced using color images of processed GPR data, **Exhibit 3.2.1-12.** The trench bottom is at approximately 8 feet.

Advanced GPRs:

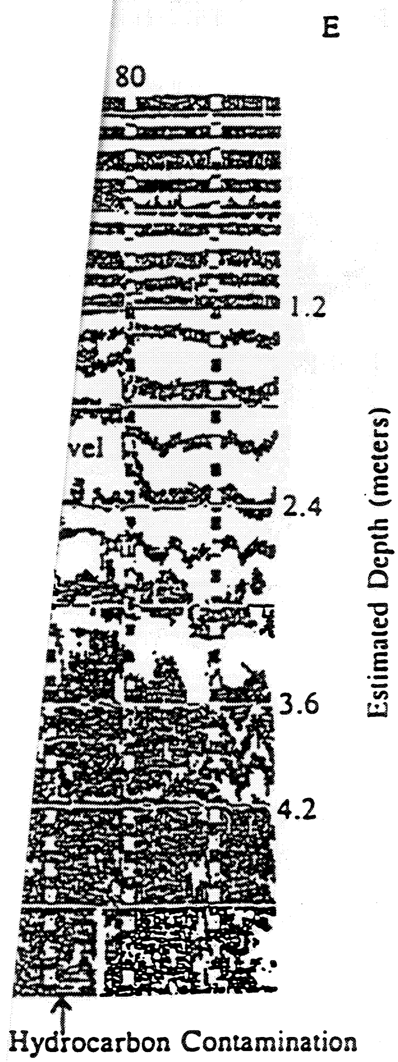
Recent advances in the GPR technology include TZ Radar, and USP Radar. The TZ Synthetic Aperture Radar with operation, say in the 1 - 3 MHz band, could provide deep ground penetration. For comparable soils, the penetration capability of this radar can be about ten times greater than for conventional radars (250 - 900 MHz) and about three times greater than the Carabas radar (20 - 90 MHz).



of dielectric constant K at probe TDR-1 with respect to background
armer colors represent a decrease in K - hence an increase in PCE
kground values. The aquitard is at 3.3 meter depth. The logarithmic
rs.



successive measurement times on probe RES-1.
e injection of PCE. The migration of the high resistivity PCE



s a dark zone of signal return on this GPR
n, 1995.

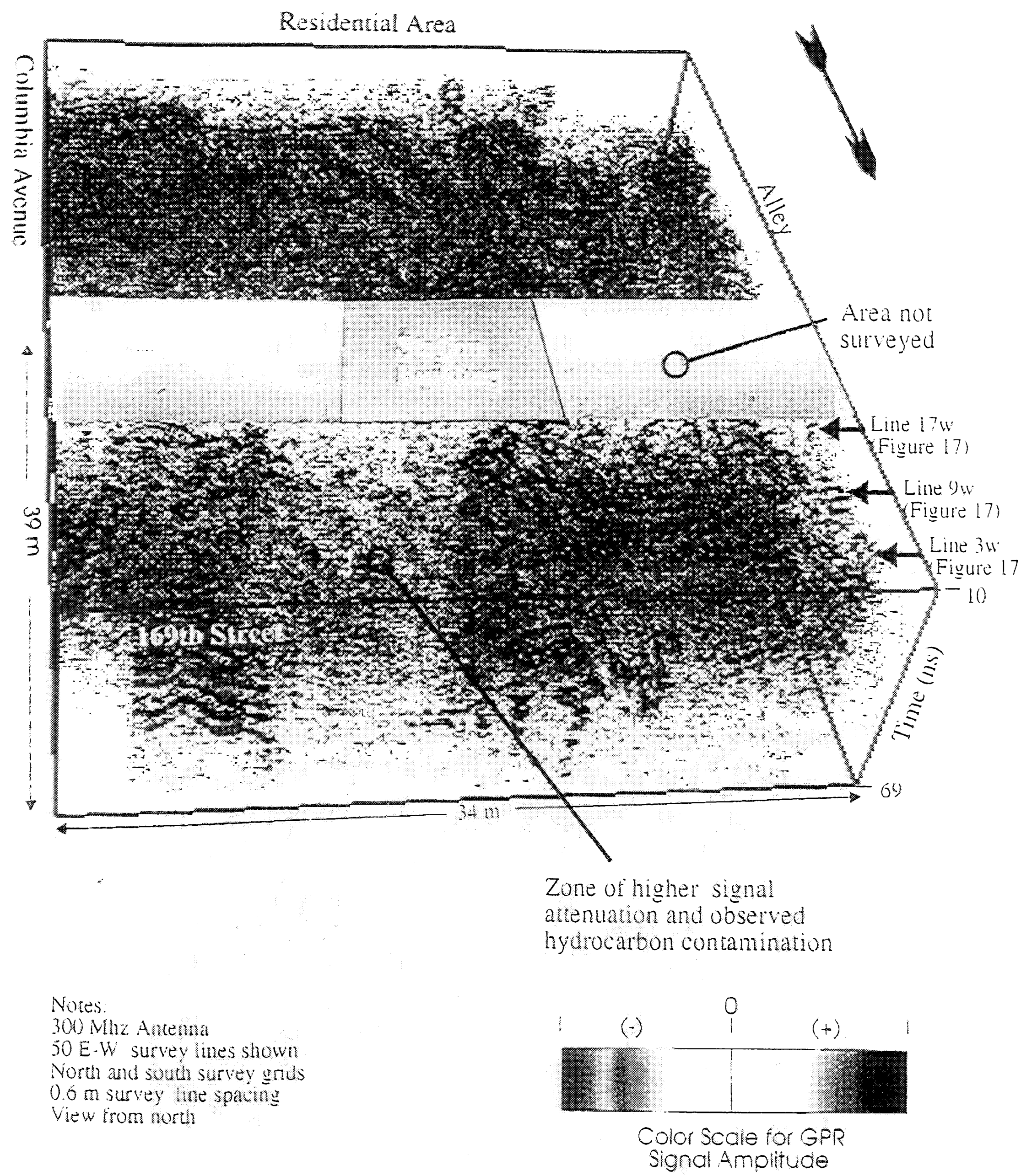
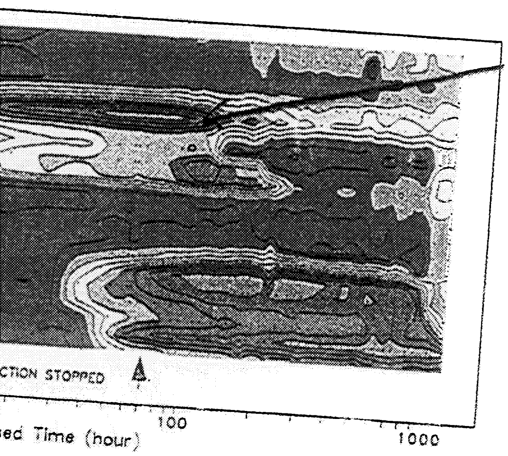
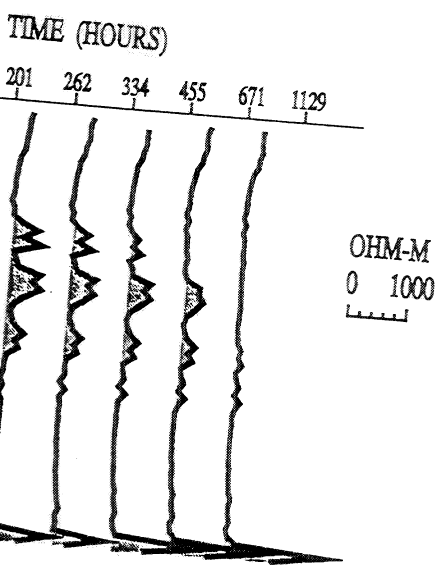


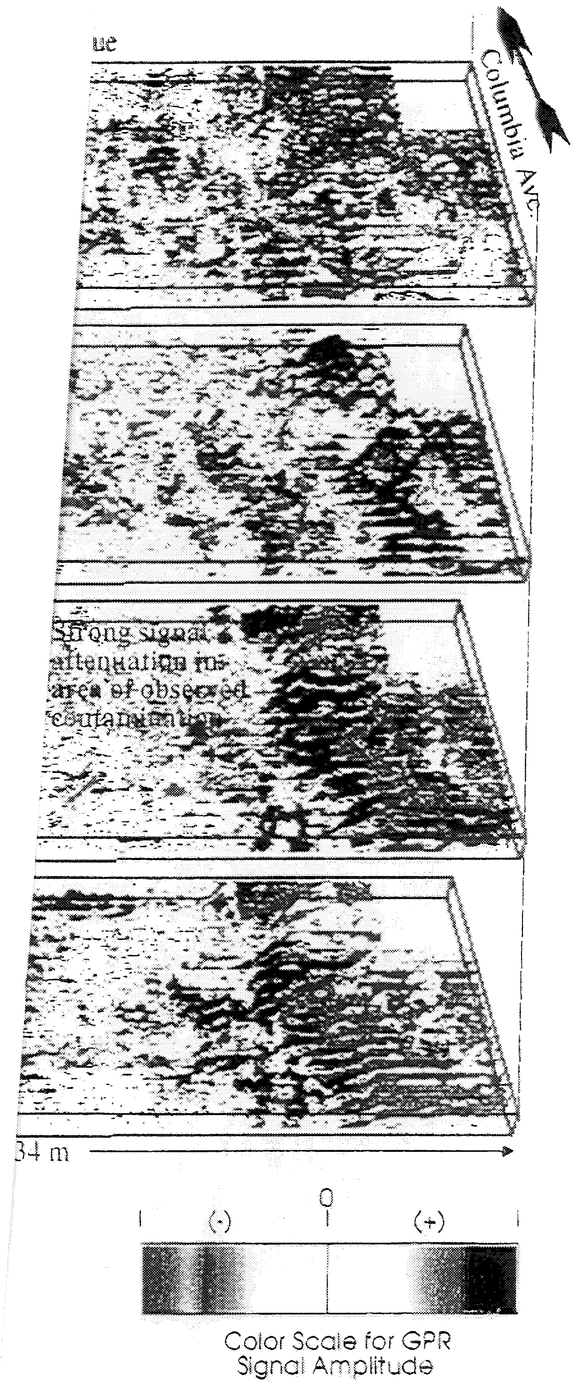
Exhibit 3.2.1-3: A 3D GPR survey over a gas station site indicates that hydrocarbon contamination has a strong effect on GPR signal properties. The hydrocarbon-contaminated zones are blanked on the records. From Daniels and Grumman, 1995.



constant K at probe TDR-1 with respect to background
represent a decrease in K - hence an increase in PCE
es. The aquitard is at 3.3 meter depth. The logarithmic



measurement times on probe RES-1.
of PCE. The migration of the high resistivity PCE



in Exhibit 3.2.1-3 accentuate the attenuation from the
tion techniques such as slicing and opacity (see 3.2.1-7)
3D volumes. From Daniel and Grumman, 1995.

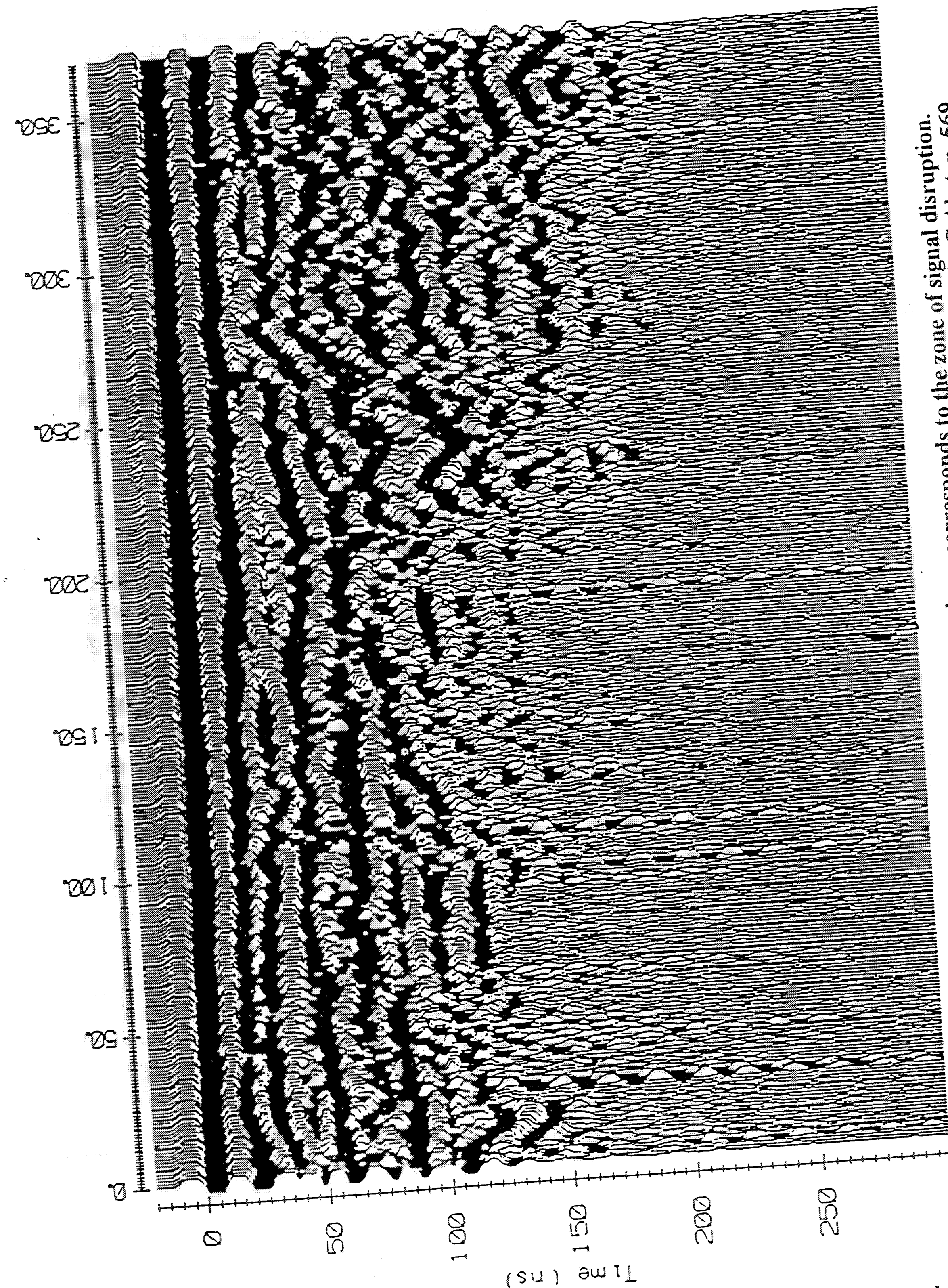


Exhibit 3.2.1-5: DNAPL plume. Contaminant plume corresponds to the zone of signal disruption. Ffrom Ulrych and Sampaio, 1994. In search of plumes: A GPR odyssey to Brazil, SEG Abst. p. 569

Exhibit 3.2.1-5: DNAPL plume. Contaminant plume corresponds to the zone of signal disruption. from Ulrych and Sampaio, 1994. In search of plumes: A GPR odyssey to Brazil, SEG Abst. p. 569

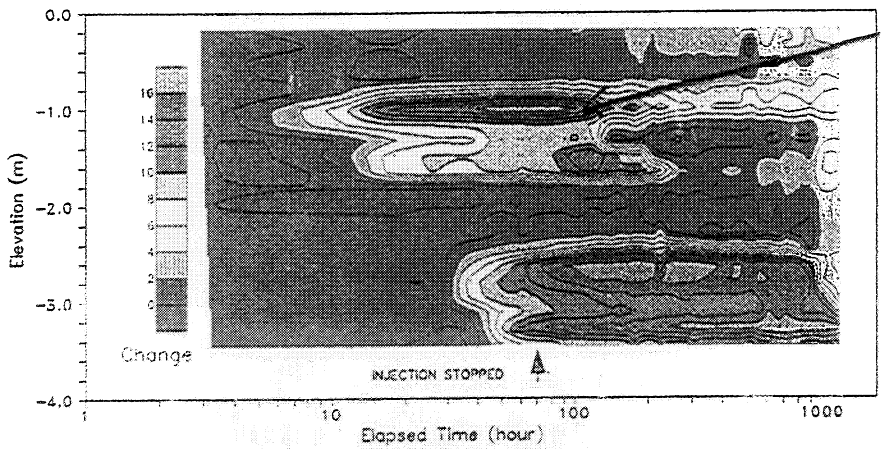


Exhibit 3.2.1-6: Time variations of dielectric constant K at probe TDR-1 with respect to background and as a function of depth. Warmer colors represent a decrease in K - hence an increase in PCE content - relative to the green background values. The aquitard is at 3.3 meter depth. The logarithmic horizontal scale gives time in hours.

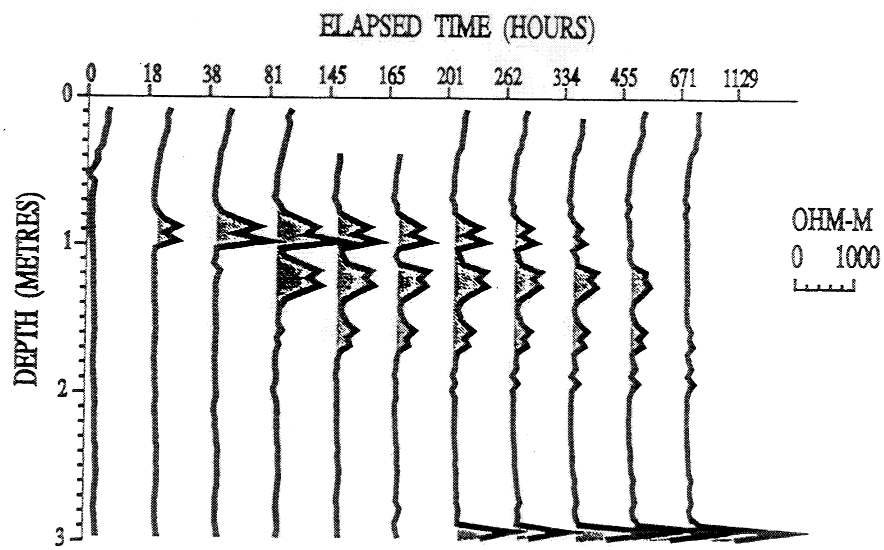


Exhibit 3.2.1-7: Variation in resistivity of successive measurement times on probe RES-1. Times are indicated in hours following the injection of PCE. The migration of the high resistivity PCE is clearly outlined.

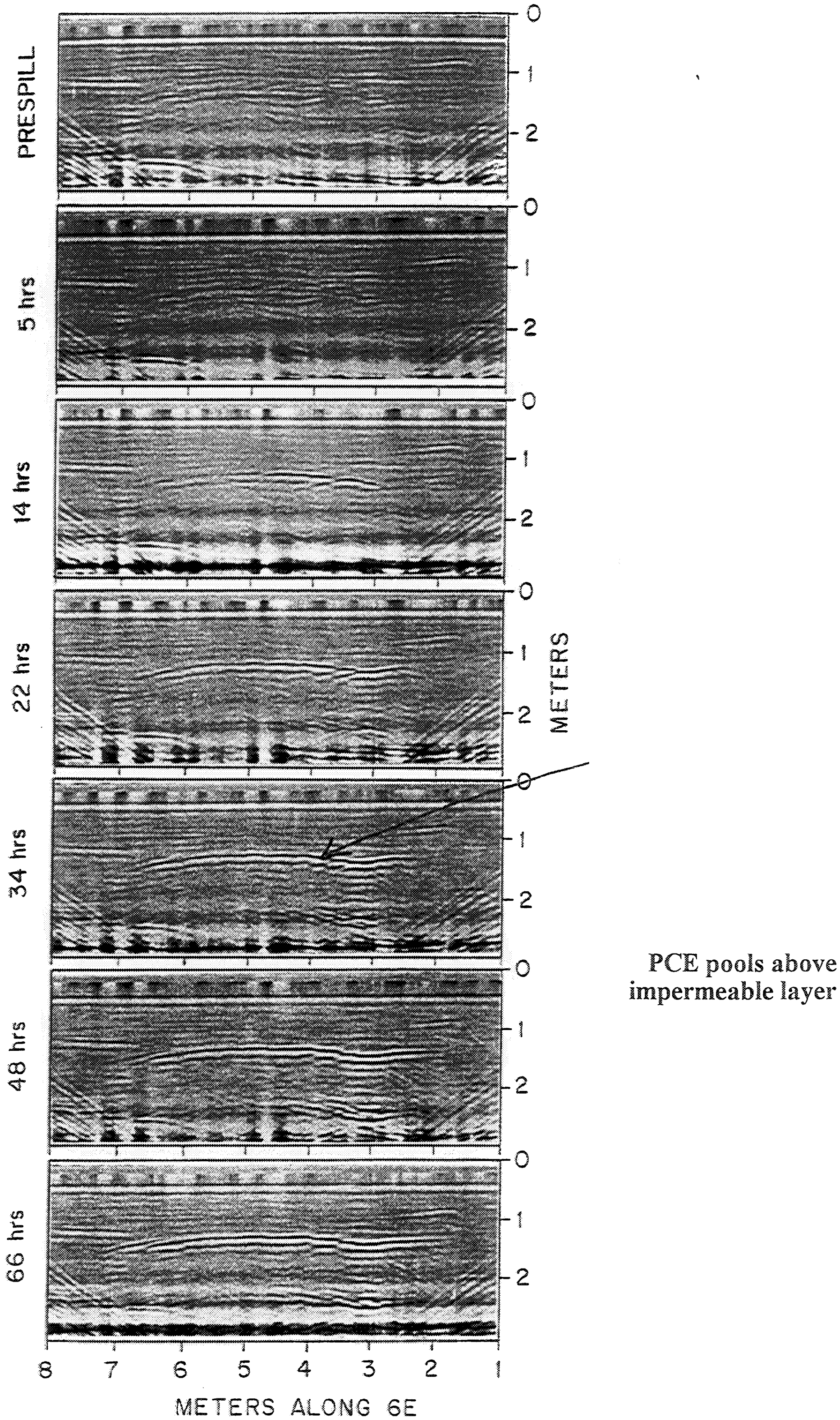


Exhibit 3.2.1-8: A section of 500 MHz radar data along line 6E. Background measurements at the top; successive measurement times given in hours. The solvent shows up as dark reflections. From Greenhouse et at., 1993.

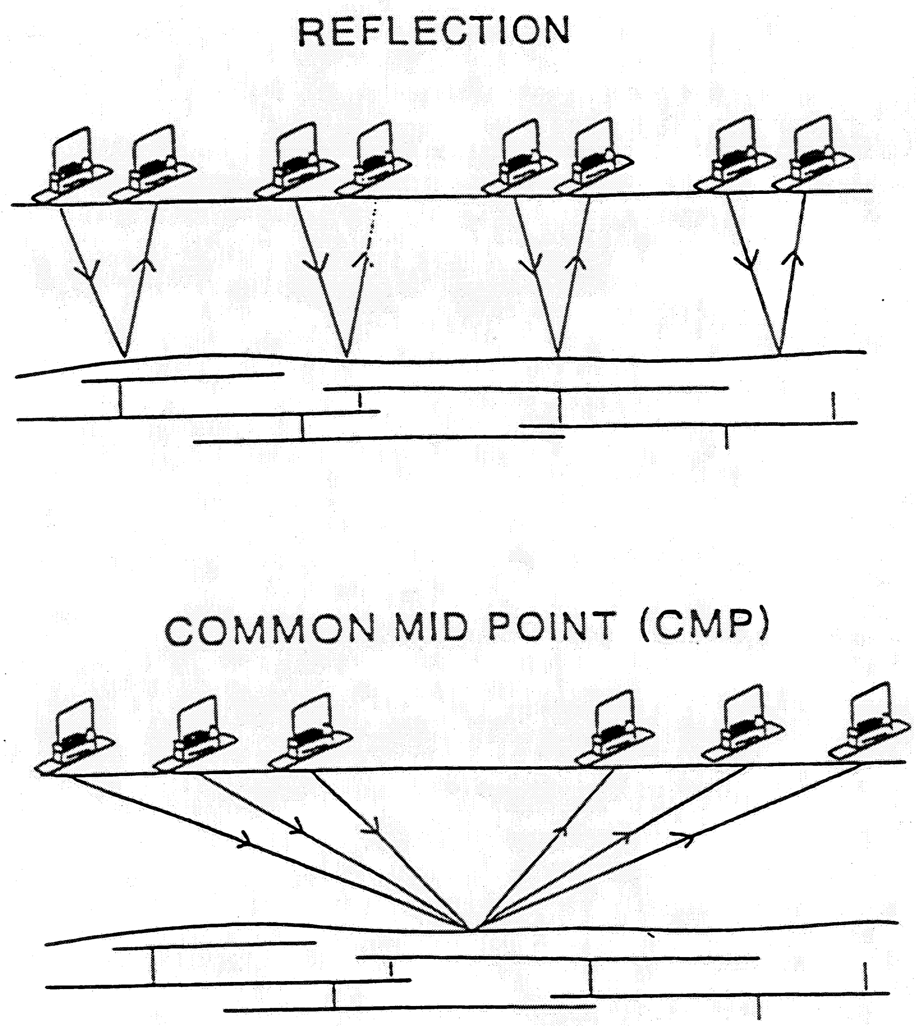


Exhibit 3.2.1-9: ***Top*** **- The standard momostatic GPR acquisition in which the transmitting and receiving antenna are close together.** ***Bottom*** **- Bistatic acquisition based on the seismic CMP model involves collecting source-receiver pairs sampling the same subsurface point at increasing source-receiver offsets. The difference in the travel time to a given reflection as a function of offset gives a measure of the velocity of the soil. From Annan and Cosway, 1992.**

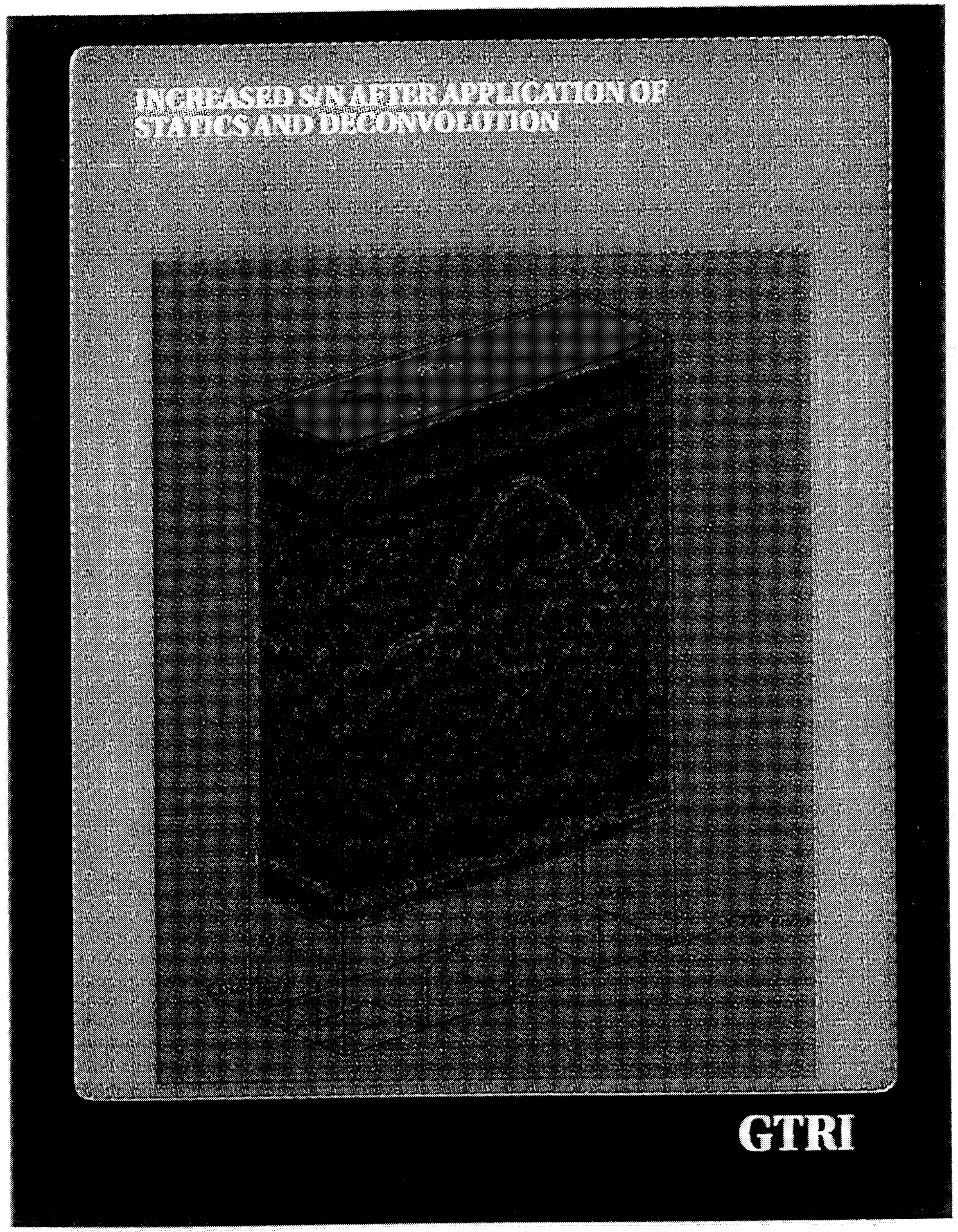


Exhibit 3.2.1-10: GPR survey conducted by GTRI across a metal pipeline. The image has been preprocessed to enhance the waveform. Compare with the final processed version in 3.2.1-7.

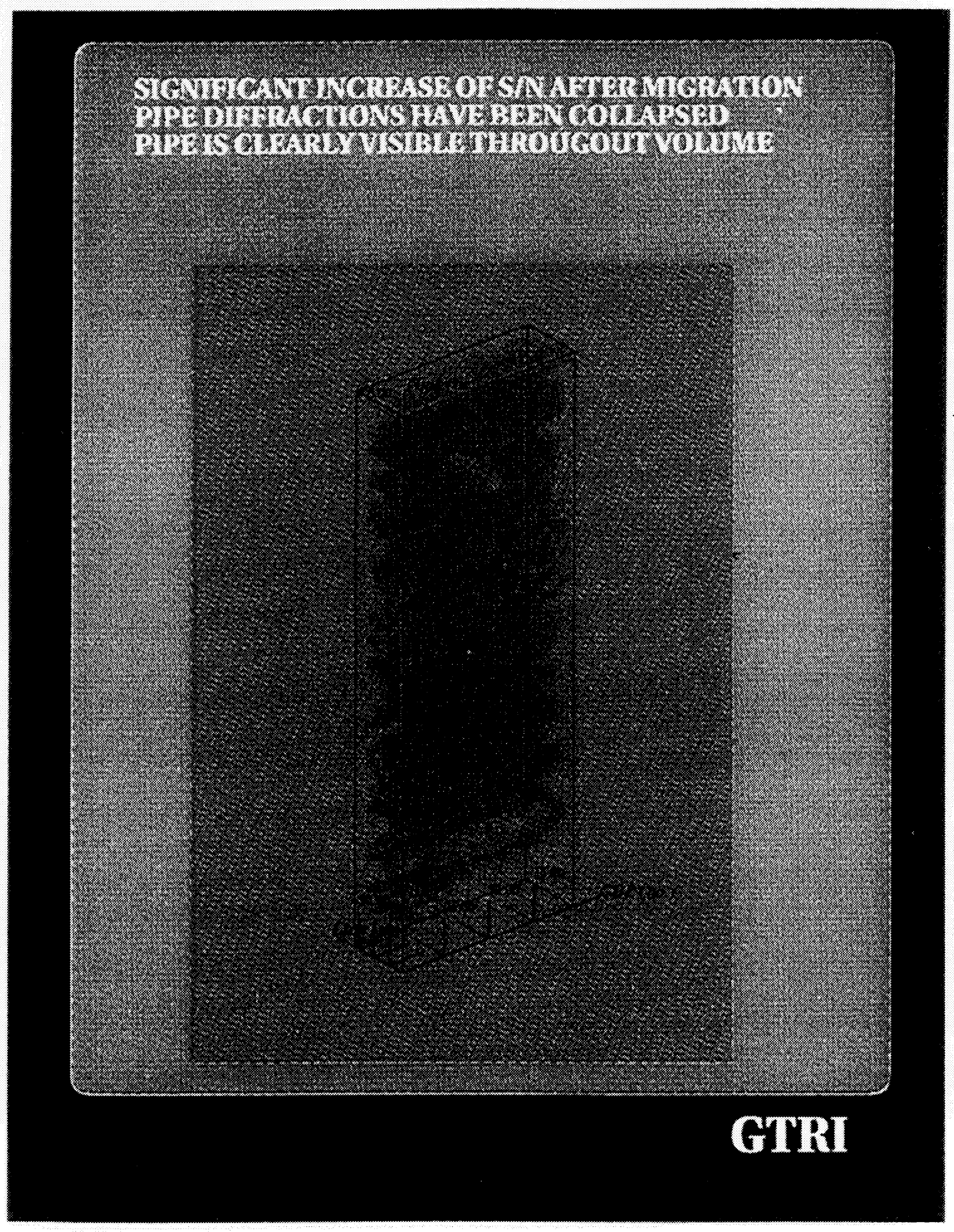


Exhibit 3.2.1-11: After migration and visualization using seismic algorithms available at GTRI, the underground pipe is unambiguously located.

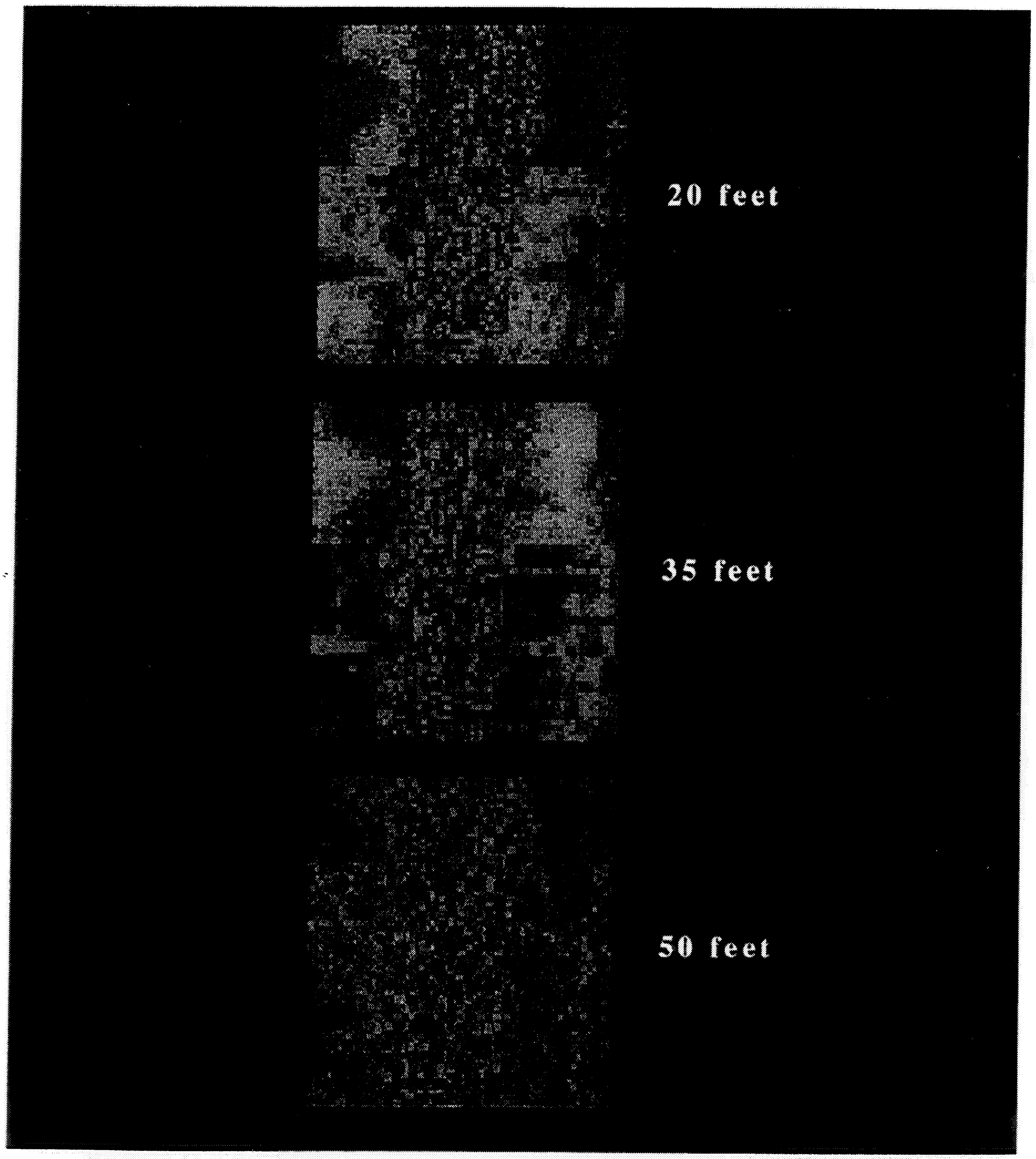


Exhibit 3.2.1-12: A trench profiled by GTRI at a Hazardous Waste site illustrates other uses of GPR for environmental remediation. The trench outline is clearly visible on the colorized records.

For an application to the MSFC site, appropriate operating band (MF / HF), antenna configuration (magnetic loop, electric dipole), modulation scheme (pulsed / FM), and operating platform (ground-mobile, fixed wing, helicopter) will be selected. Choices among these options would in part depend on the properties of the soil at the site. The TZ radar can also be operated in the short pulse mode to capitalize on the advanced concepts incorporated in the USP radar, described below.

USP Radar:

The USP radar is an improved version of the impulse GPRs and provides two capabilities not available in other designs: *(a)* RF pulses crafted to obtain optimum propagation and matched to both the medium and target, and *(b)* RF pulses which are shorter in duration than the relaxation time of the medium. Under certain well-defined conditions, it is expected that significant penetration will be obtained through media normally absorptive or dispersive. In terms of the measurements, two measurements are of interest with the traditional subsurface radars. One is wave attenuation as a function of frequency, and the second is velocity of wave propagation versus frequency. In the present approach, we calculate a third, namely: the wave dispersion as a function of frequency.

A rule of thumb for CW signals is that the attenuation of electromagnetic radiation rises with frequency and that at a given frequency wet materials exhibit a higher loss than dry ones. In the present instance, impulse, not CW, signals are addressed, and it is expected that there are major differences between CW, FMCW, stepped FM and impulse signals (Barrett, 1991). Unfortunately, the overwhelming amount of data on dielectric effects has been obtained with CW signals, so impulse effects with pulses shorter than the relaxation time of the material are seldom available.

To give a feel for the losses to be expected, some data obtained with CW signals, not short pulse signals, are shown in **Exhibit 3.2.1-13.**

Almost all subsurface radar systems presently operate at frequencies below 1 GHz as the attenuation increases with frequency. The conventional wisdom is that the earth acts as a low-pass filter. However, this conventional wisdom neglects two aspects of the problem: *(I)* soil is also a dispersive medium, and the low frequencies in the returned signal at the surface can either be due to low-pass filtering or medium dispersion; *(ii)* the relaxation times of the earth media are comparatively long, therefore short pulse envelope effects may occur (Barrett, 1991, 1995). The processing procedures proposed for the next phase of the project will exploit the possibility of increased penetration using matching of the pulse to the media characteristics.

Exhibit 3.2.1-13: Attenuation. Premittivity and Penetration vs. Frequency for selected materials. Davis and Annal, 1989

Media	Frequency	Loss at constant wavelength	Permittivity at constant wavelength	Penetration vs. Frequency	
				Penetration Depth	Maximum Frequency Used
wet clay soil	100 MHz (single transit)	20-30 db m^{-1}	5-40	2 m	100 MHz
wet clay soil	1 GHz	100 db m^{-1}	5-40	2 m	100 MHz
sea water	100 MHz	200 db m^{-1}	80		
sea water	1 GHz	300 db m^{-1}	80		
fresh water	100 MHz	4 db m^{-1}	80	100 m	100 MHz
fresh water	1 GHz	40 db m^{-1}	80	100 m	100 MHz
ice, fresh water	1 GHz	1 db m^{-1}	3-4	10 km	10 MHz
ice ,sea water	1 GHz	50 db m^{-1}	3-4	10 km	2 MHz
sandy soil	1 GHz	10 db m^{-1}	3-5	3 m	1 GHz
loamy soils	1 GHz	20-30 db m^{-1}	4-8	3 m	500 MHz
desert sand	1 GHz	1 db m^{-1}	3-5	3 m	1 GHz
water		4-40 db m^{-1}	80		
most soils			2-6		
soil- water mixtures			4-40		
higher temperature pure ice			3-4	1 km	2 MHz
sand (desert)			3-5	5 m	1 GHz
salt (dry)			5-6	1 km	250 MHz
coal				20 m	500 MHz
rocks			4-6	20 m	50 MHz
walls				0.3 m	10 GHz

3.2.1.1 Subterranean Imaging with USP Ground Penetrating RF Sensor

The following examples were obtained with short pulse (1 - 5 nanosecond duration) GPRs, which used, however, nonoptimum (unmatched to medium) pulses.

Imaging Geological Strata:

All discontinuities shown in **Exhibit 3.2.1.1-1** to **Exhibit 3.2.1.1-12** are due to sharp changes in the dielectric properties of the medium. Imaging buried metallic objects is quite straight forward and the signal-to-noise can be increased by magnetic techniques which interact with the buried object and provide a stronger radar return, or, if the metallic object, *e.g.*, a pipe, can be reached above ground, by conducting current along the pipe, which also provides a stronger radar return. **Exhibits 3.2.1.1-6** and **3.2.1.1-9** indicate that by just changing antennas (100 MHz pulsed monocycles versus 25 MHz pulsed monocycles for **Exhibit 3.2.1.1-6**; 12.5, 25, 50 and 100 MHz pulsed monocycles for **Exhibit 3.2.1.1-9**), various features of the terrain can be brought into focus, and other features diminished in resolution. Thus, if even a modest selection of radiated components, (which are selected by the filtering action of the different antennas); provides the selective interaction of the transmitted radiation with either metallic objects or ground strata, then crafting pulses with an optimum selection of radiated components will have an even greater effect in bringing to sharp focus some elements of the field irradiated and playing down other; and under other requirements, bringing to sharp focus those elements previously played down and playing down those elements brought previously to sharp focus. **Exhibit 3.2.1.1-8** indicates an example of leaching from a municipal landfill detected by pulsed GPR, and **Exhibits 3.2.1.1-10 and 3.2.1.1-11** show the detection of subterranean watertables by the same technique. The strata below a paved road is readily mapped in **Exhibit 3.2.1.1-7**.

Exhibit 3.2.1.1-12 indicates the importance of data processing, and also the importance, sometimes, of neglecting the processing for a realistic picture using pulsed GPR. The elliptical signatures from buried objects are easily detected by the eye. Therefore, although artifacts, such signatures have a use in object detection. However, it is also true that realistic soil formations are viewed after removal of artifacts including envelopes. All three methods of representation shown in **Exhibit 3.2.1.1-12** have their uses. Therefore, data should be multiply processed with a view to subsequent use.

The advantage of short pulse techniques, and even more so, of optimized short pulse techniques, is that not only is the medium penetrated and a radar return obtained, but that return has maximum resolution of the subterranean strata and reflecting objects. In the case of leakage from storage barrels, it is expected that the leaking fluids will change the dielectric properties of the surrounding soil. By using short pulse techniques optimized for maximum resolution, fluid leaks may be detected in many cases as dielectric discontinuities **(Exhibit 3.2.1.1-8).**

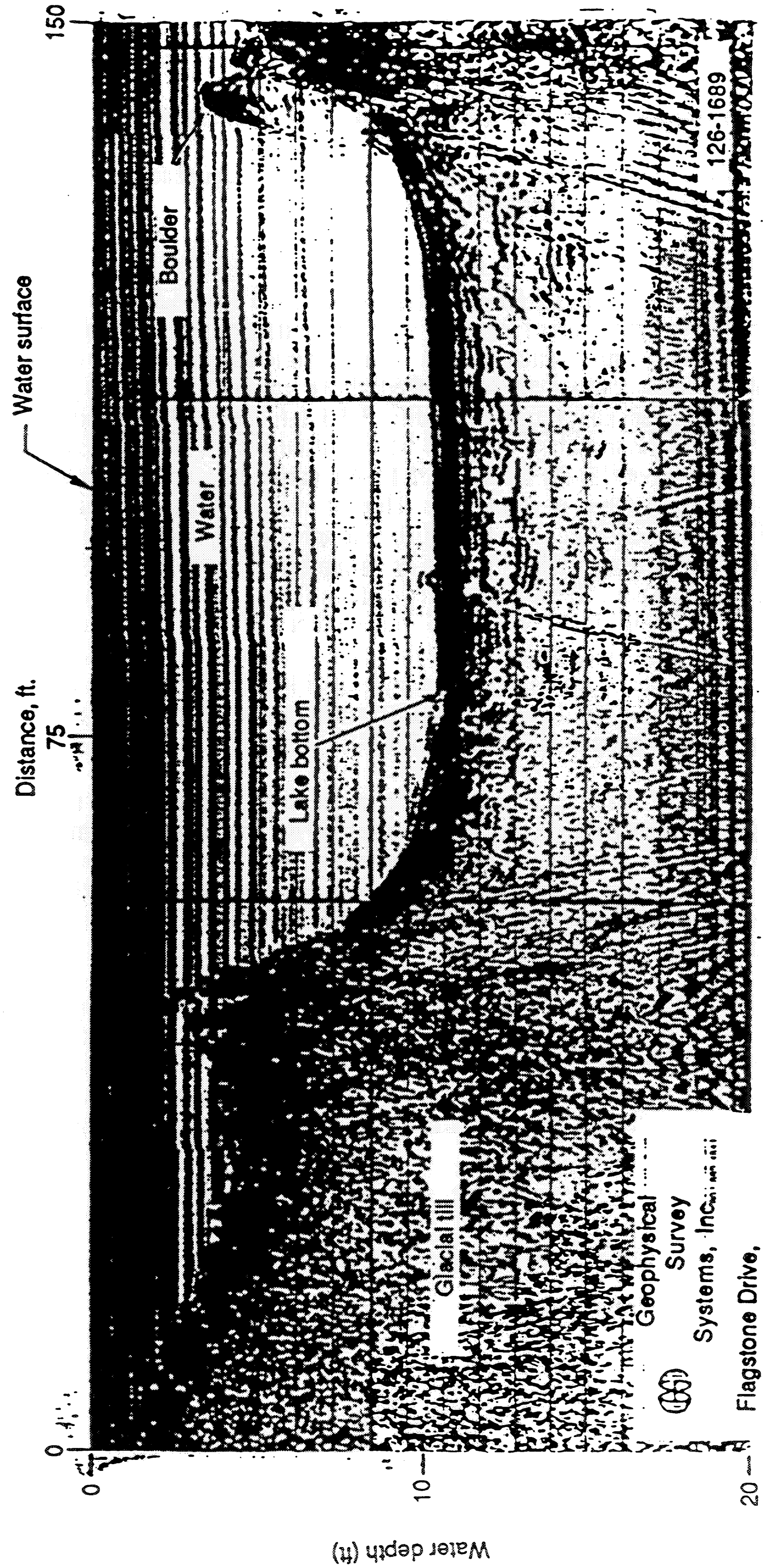


Exhibit 3.2.1.1-1: From Geophysical Survey Systems, Inc.

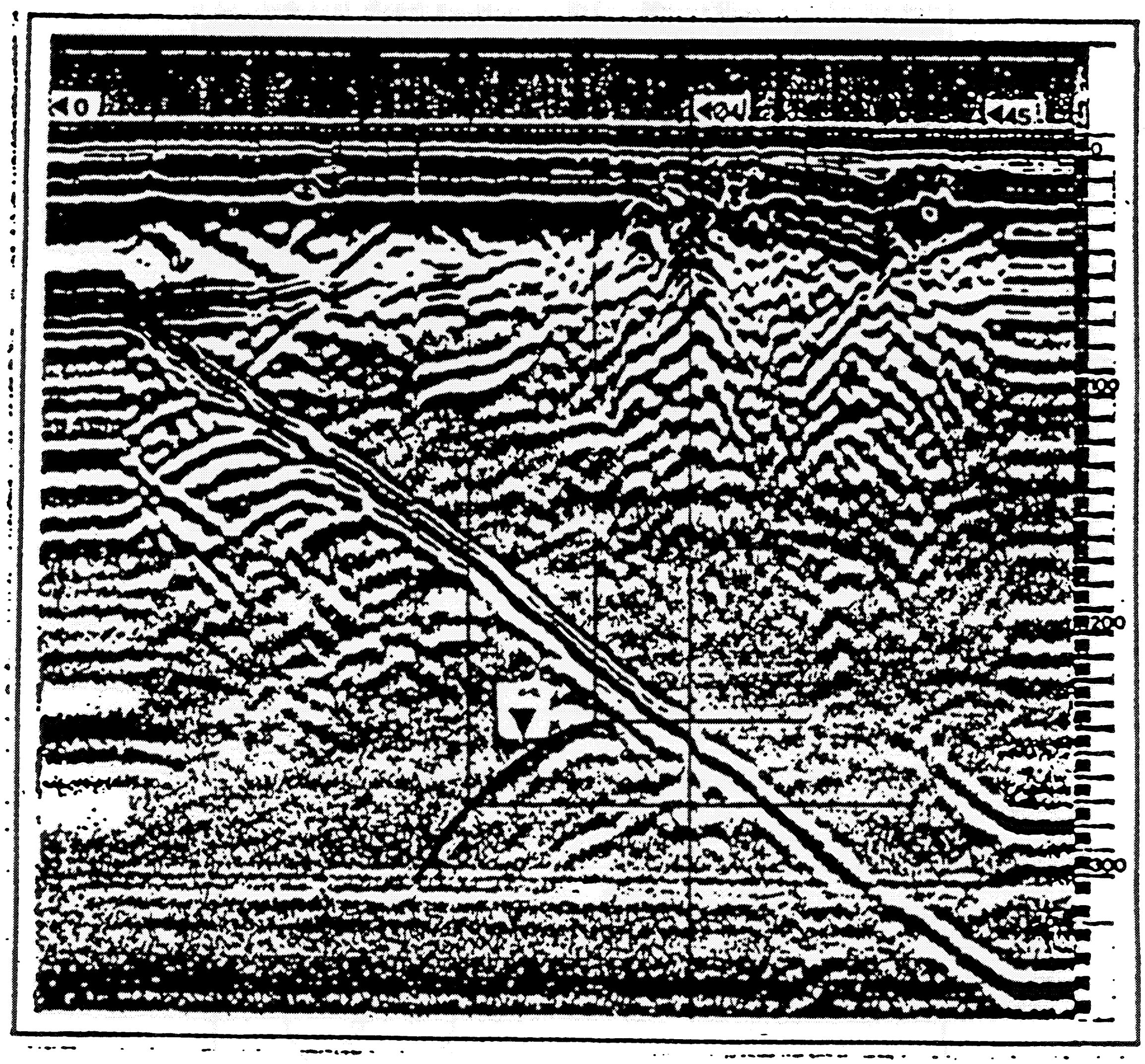
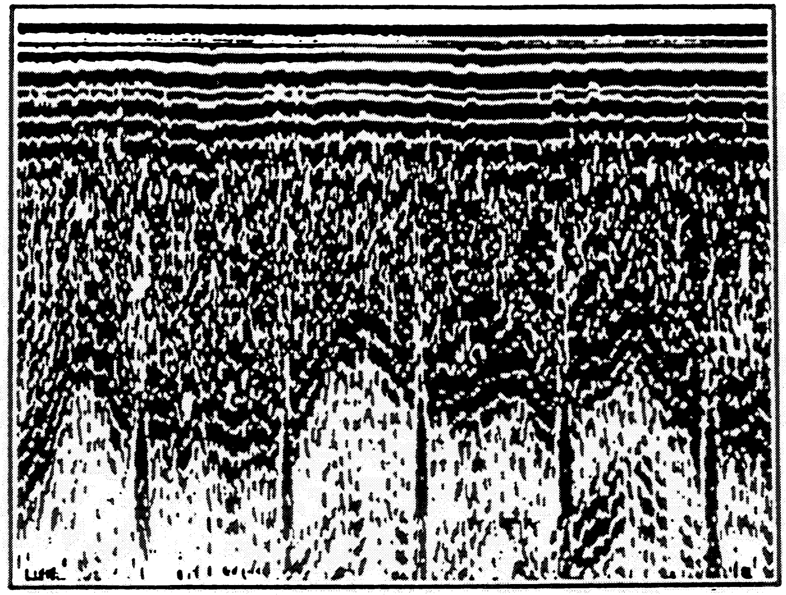


Exhibit 3.2.1.1-2: Dipping fracture at Finnsjön in Uppland, Sweden. The label '⌀4' indicates the position of a core-drilled hole. The rock is granodiorite for which the estimated RF wave velocity is 1.03×108 m/s at 10 MHz. The velocity of propagation determined by the reflection from the point-source reflection at the center of the record is 1.03×108 m/s. The intersection of the drill hole and the fracture zone is 9.9 m, From Ulriksen (1981).



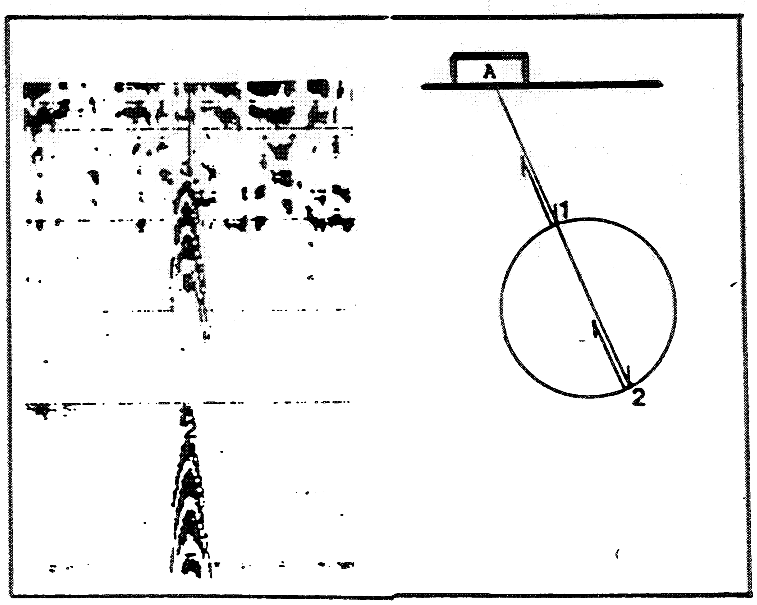
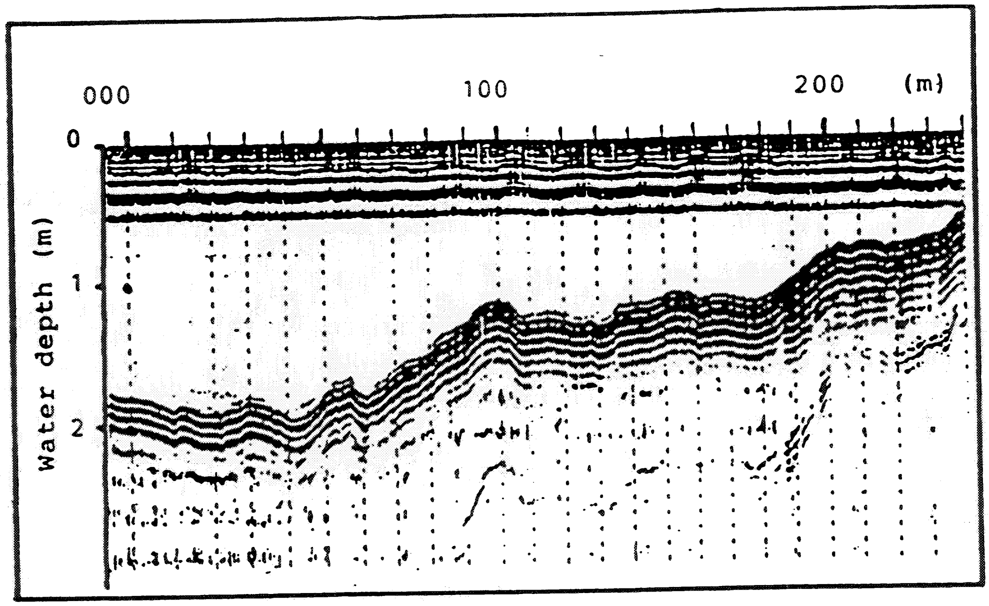


Exhibit 3.2.1.1-3: *Upper:* radar profile showing drainage pipes and the associated ground water table in a drained peat bog. From Ulriksen (1980). *Lower:* radar returns from the upper and the lower part of a 300 mm concrete drainage-pipe which is water filled.



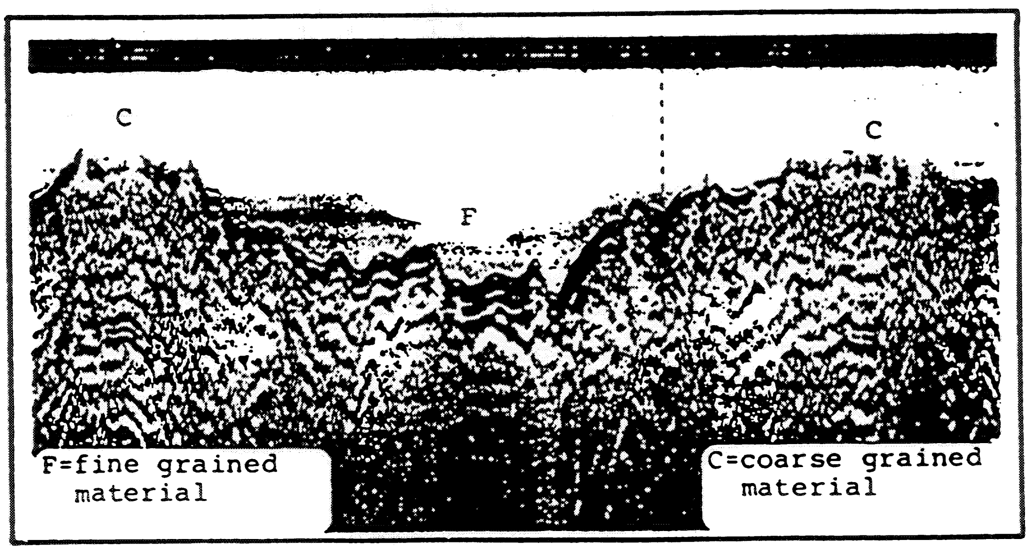


Exhibit 3.2.1.1-4: ***Upper:*** **radar profile of water depth recorded from the ice surface at Kranesjön in Skåne. The appearance is due to the RF energy being trapped between two highly reflective interfaces** ***Lower:*** **record with 80 MHz antenna towed behind a boat in a water-filled gravel pit.**

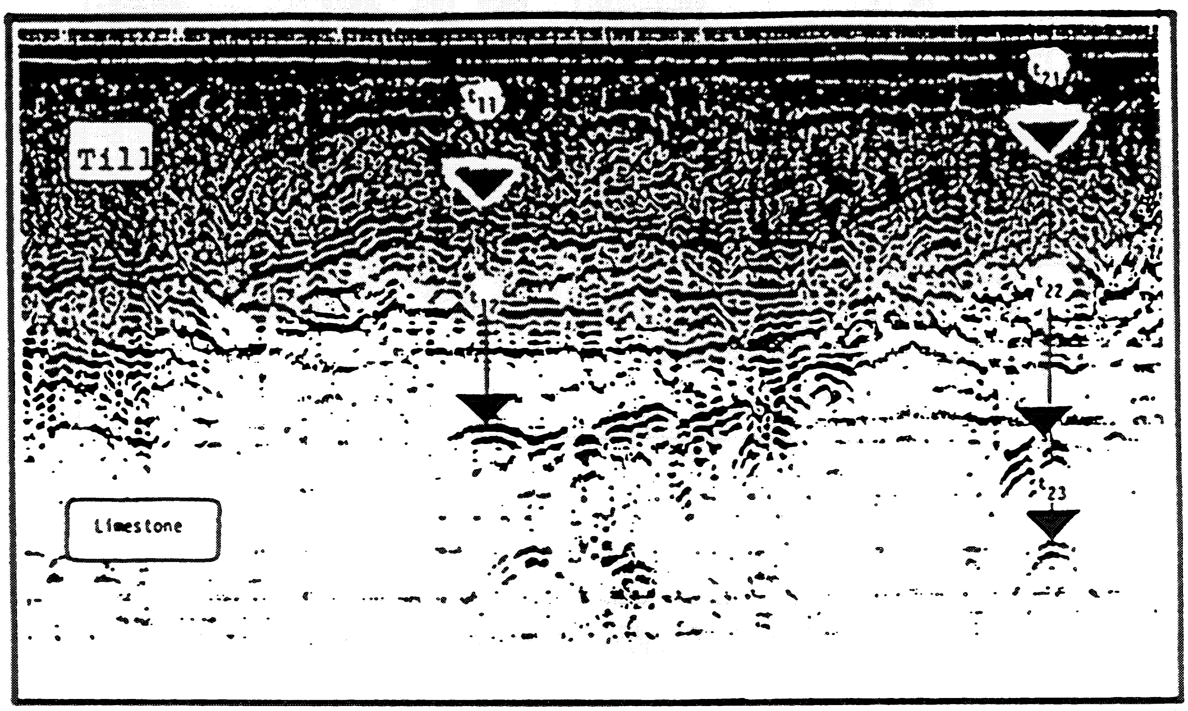
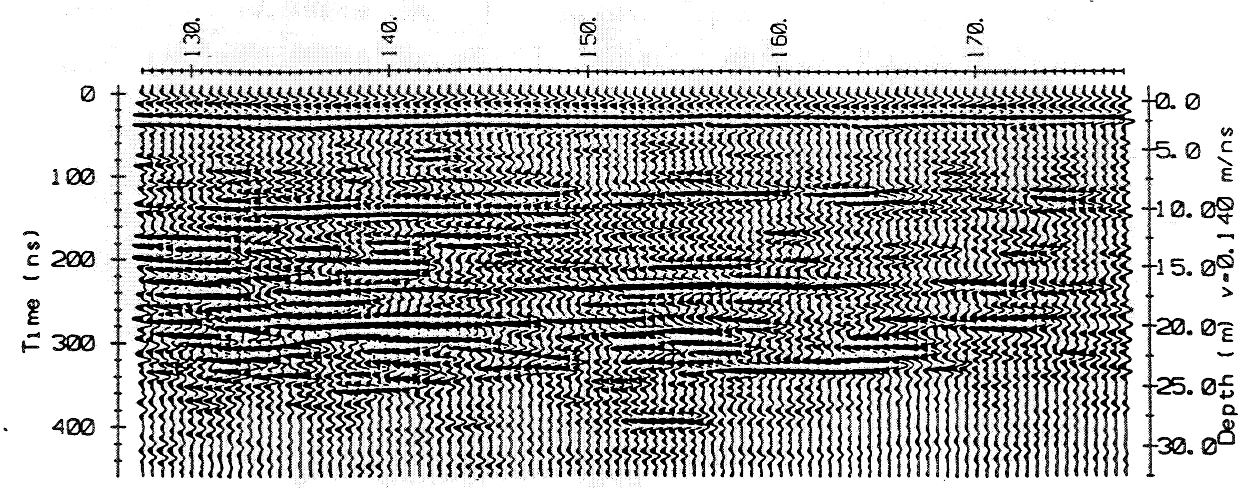
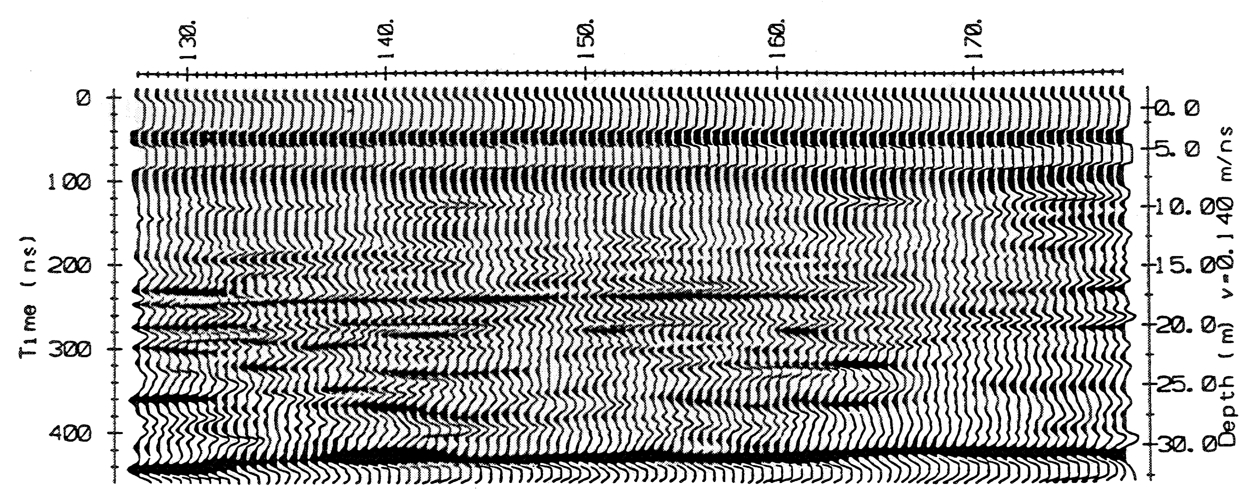


Exhibit 3.2.1.1-5: Radar profiles recorded at Ingnaberga, Skåna, Sweden, showing cavities in limestone. The limestone lies under a layer of till. Assuming a relative permittivity of 9 in the dry moraine and 4 in the equally dry limestone, the left cave's roof is 10.7 m below the surface and the right cave 's roof is 12.4 m below the surface. From the right cave there were two echoes which were interpreted as reflecting from the roof and the floor of the cave. The estimated height of the cave is 7.4 m. From Skanrad, et al, 1981.



A.

100 MHz



B.

25 MHz

Exhibit 3.2.1.1-6: ***A.*** **The 100 MHz data exhibits many distinct events which become blurred when the frequency is lowered to 25 MHz.** ***B.*** **These data were acquired over two tunnels in an area of gneissic bedrock. The rock texture had a spatial scale of 30 cm. At 100 MHz the clutter is clearly visible. At 50 MHz much of the clutter from the rock texture is suppressed**

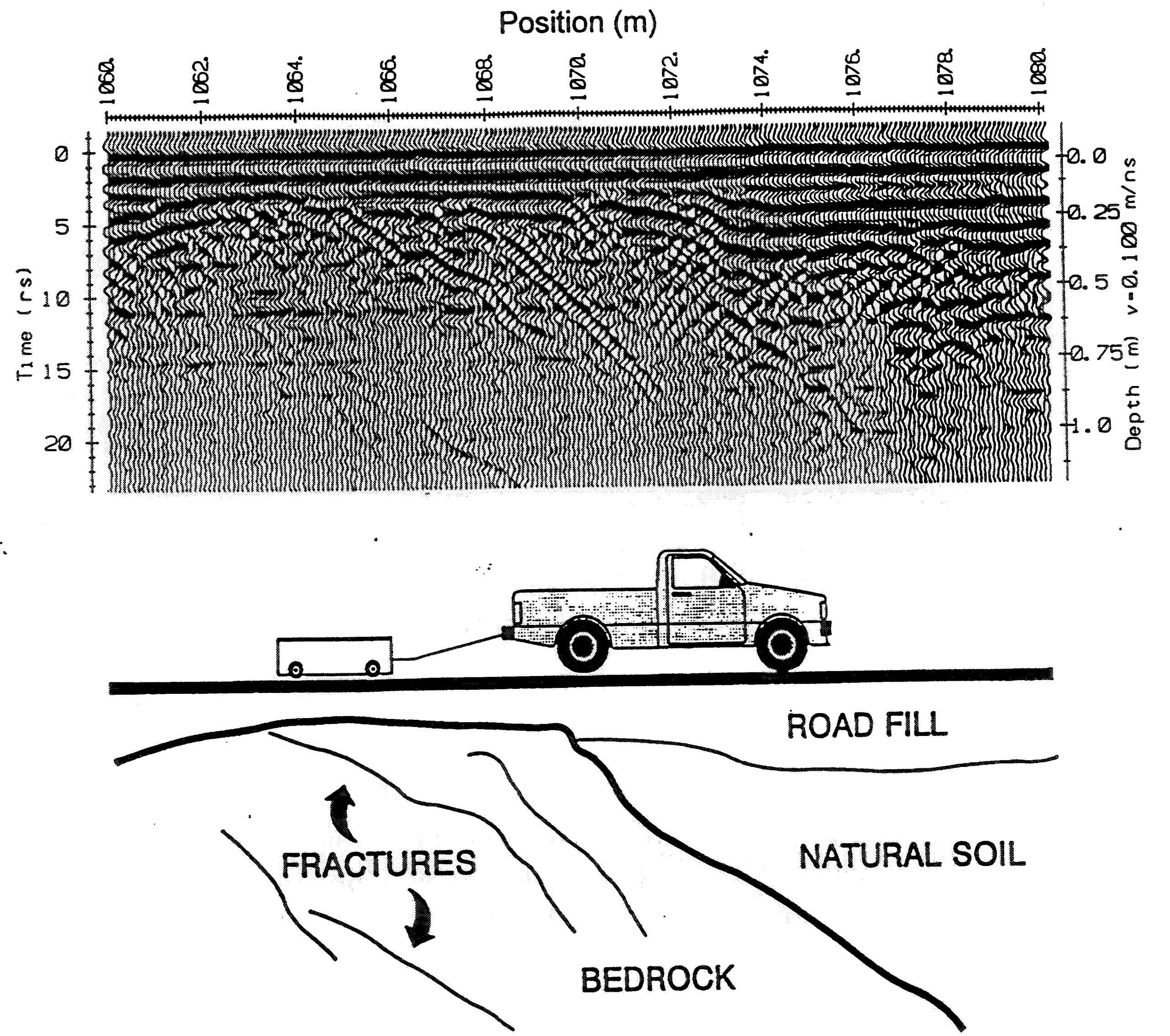


Exhibit 3.2.1.1-7: These data were acquired along a paved road in Sweden using a pulse EKKO 1000 system with 900 MHz center frequency antennas. There is detailed definition of bedrock knob which crests at the base of the road bed between 1061 and 1070. Beyond 1074 the normal fill and thicker road base course, typical of the majority of the road, is observed.

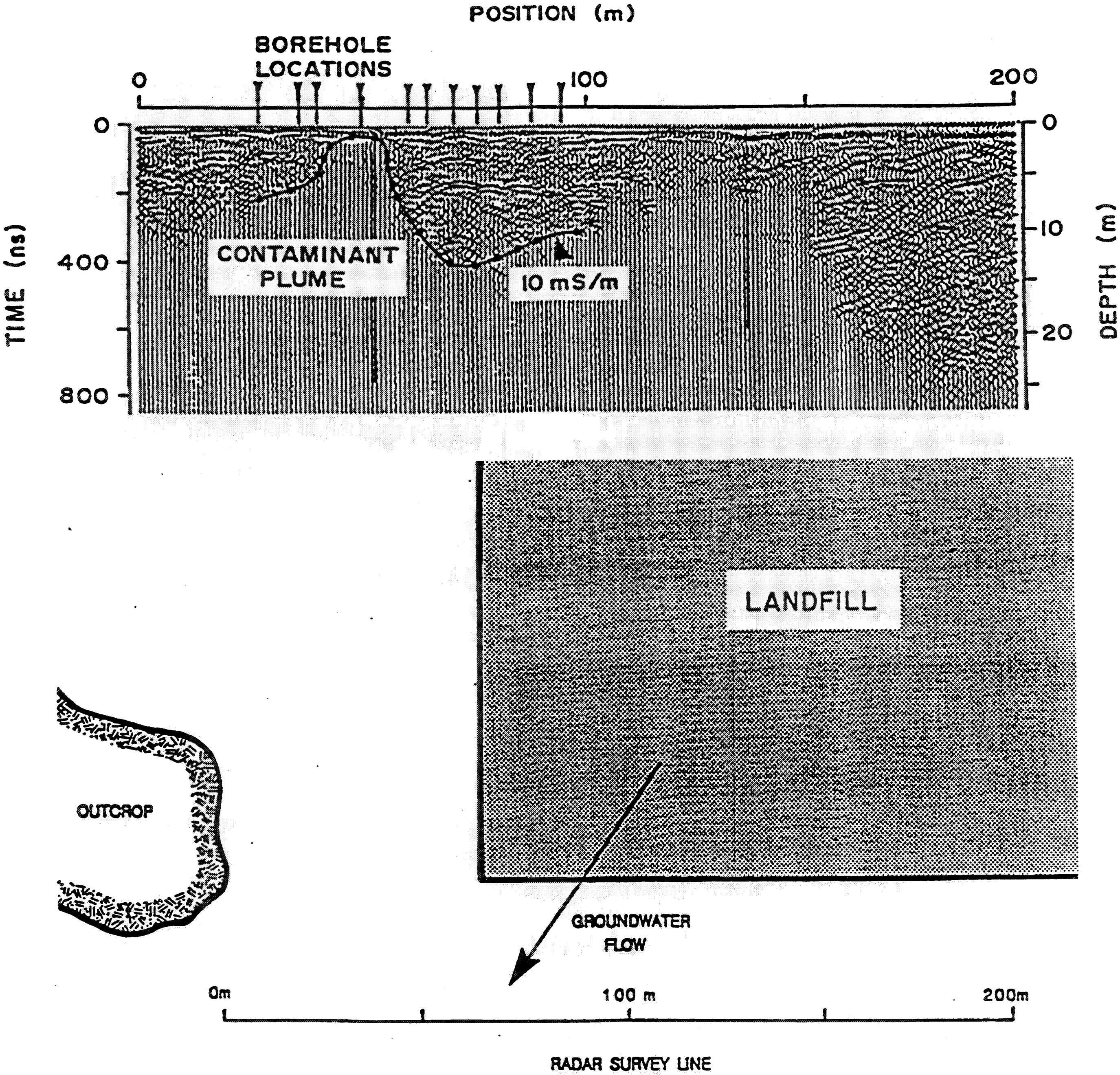


Exhibit 3.2.1.1-8: These data were acquired down groundwater flow direction from a municipal landfill site. The landfill had been created by depositing municipal garbage into an old sand and gravel pit. Subsequent decay of the material had resulted in a leachate plume extending down ground and water flow direction to a nearby stream. The high chloride content in the groundwater results in a high electrical conductivity for the pore water in the soils. In areas where there are high concentrations of the leachate contaminate, the radar signals are highly attenuated. The above section is a classic example of how radar can be used to study contaminate distribution in such a situation.

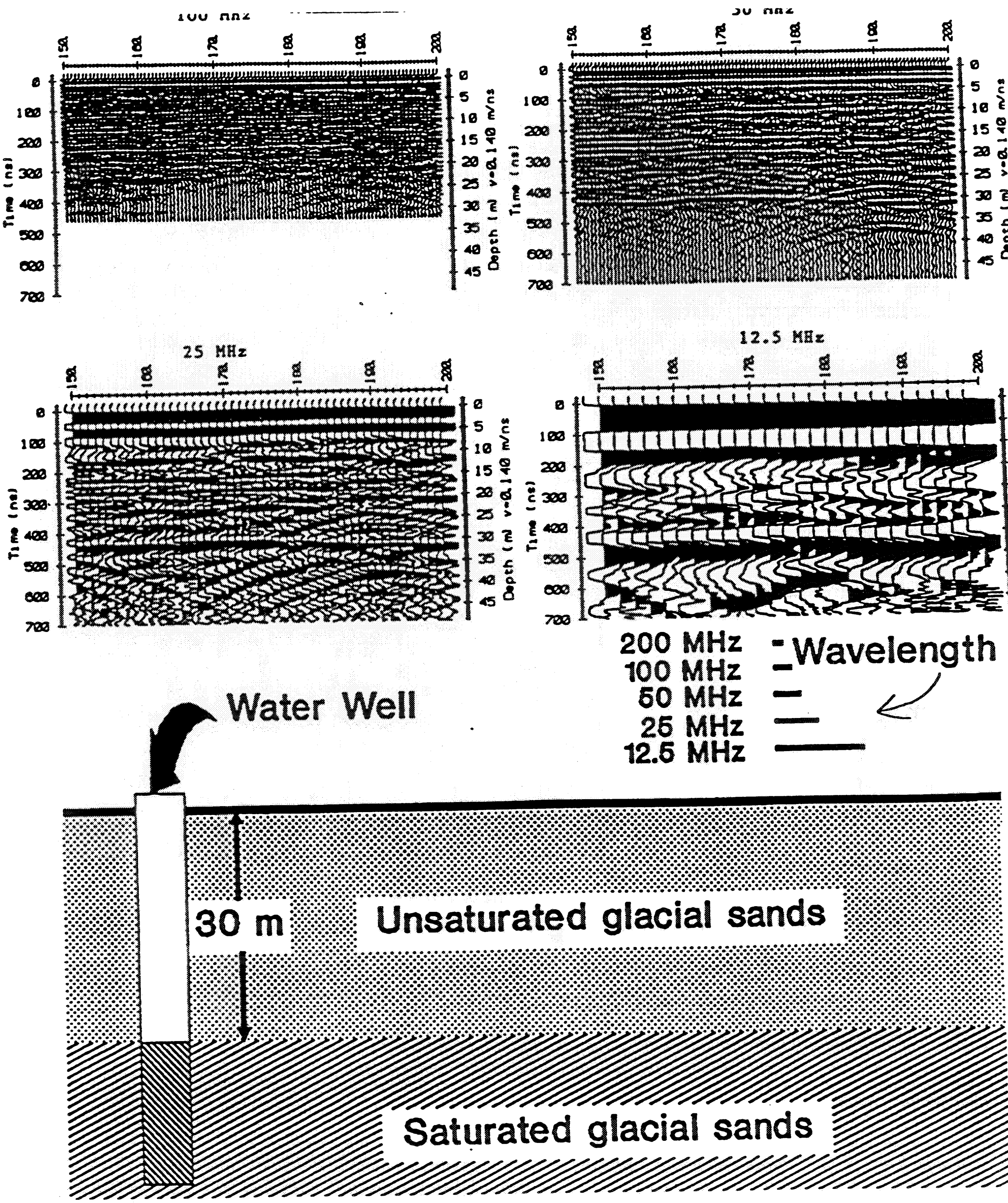


Exhibit 3.2.1.1-9: These data were acquired at a site in Holland. The objective was to map the water table. The variation of frequency results in a tradeoff between depth of exploration and resolution of stratigraphy which these example clearly indicate.

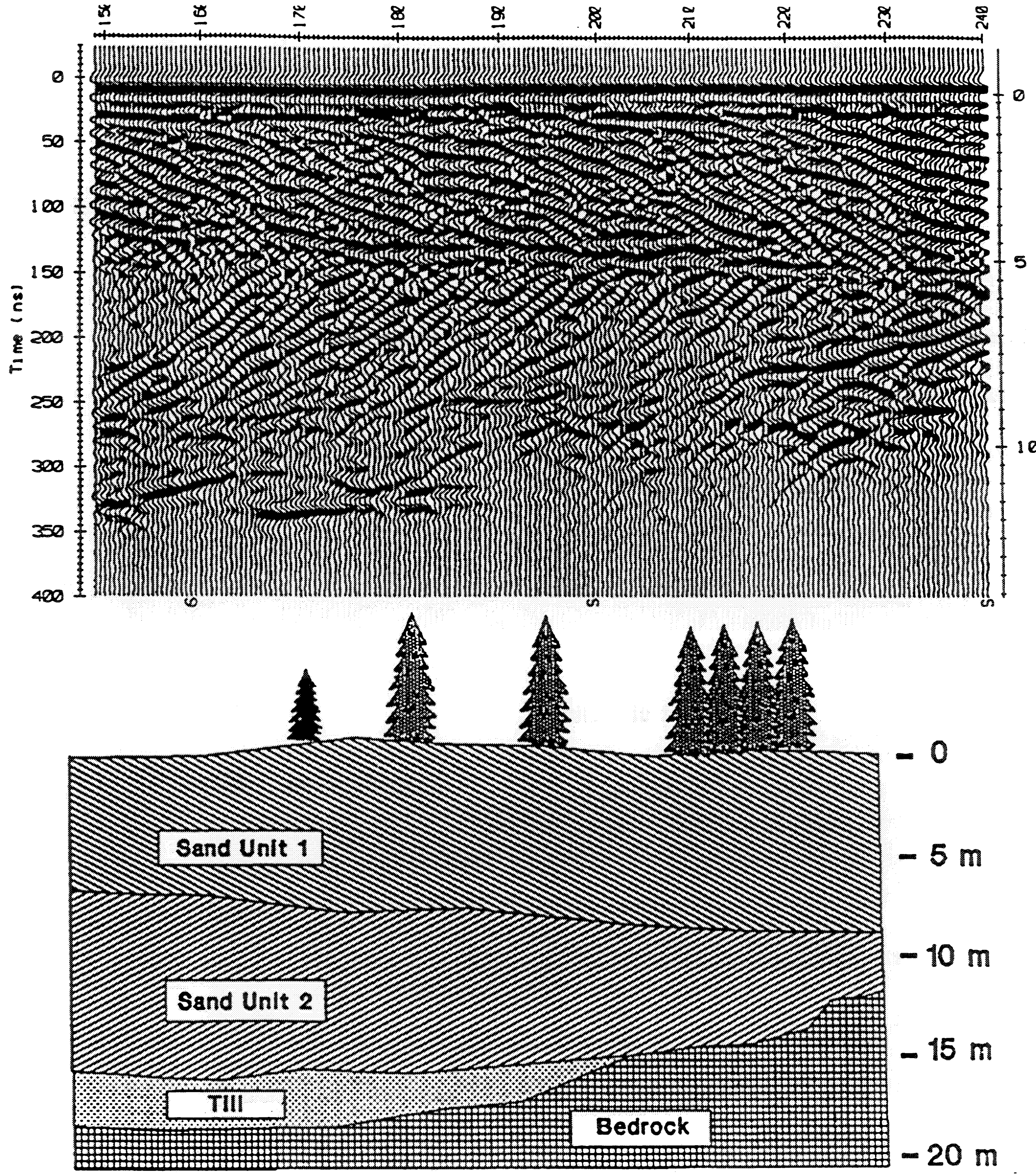
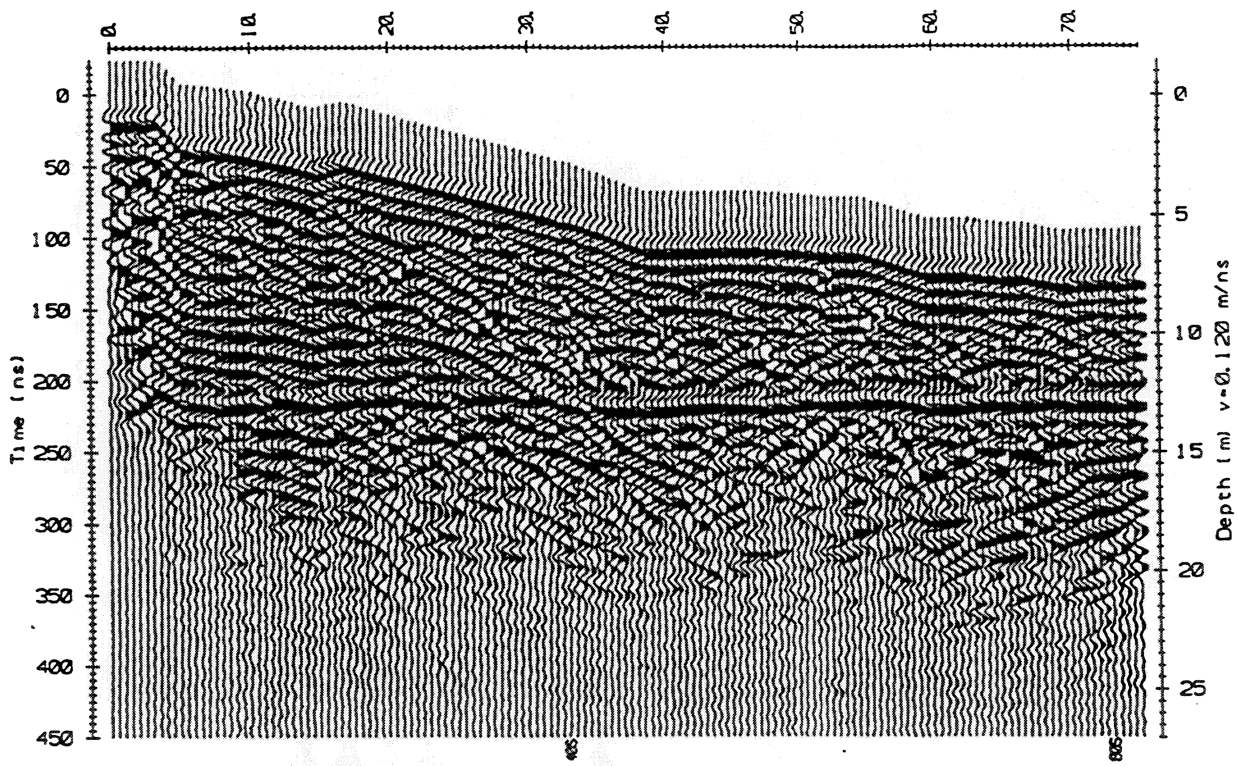


Exhibit 3.2.1.1-10: These data are from a shoreline deposit in northern Canada. The unique features in these data are the strong return from the erosional unconformity. The dip of the bedding in sand unit #1 is totally different from the dip in the bedding in sand and gravel unit #2 and the contact between the two units is also a strong GPR reflector. A till layer and the bedrock is still visible in this section. These data were acquired in conjunction with the siting of a pulp and paper waste water lagoon.



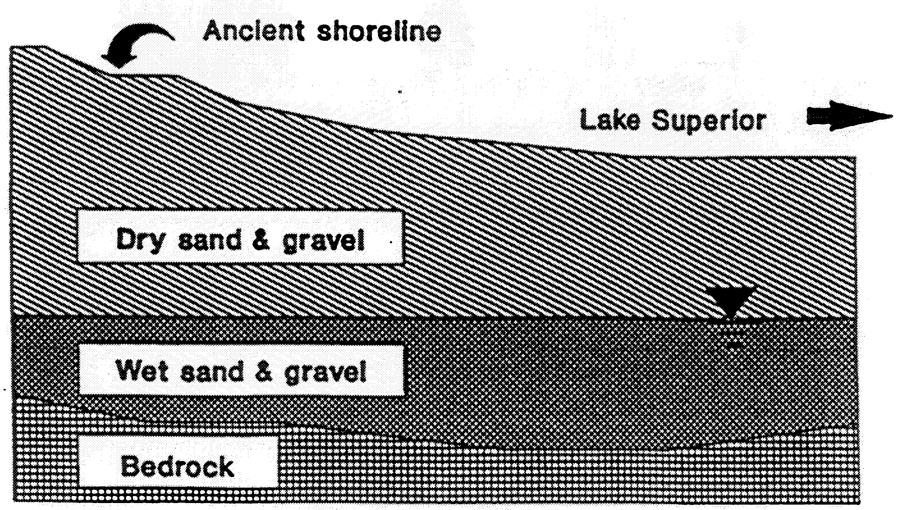


Exhibit 3.2.1.1-11: These data illustrate the use of a pulse EKKO system for mapping water tables. The water table is a very strong radar reflector and has a negative coefficient associated with it. Both the polarity of the reflection coefficient as well as its variation across the section are clearly visible in this data set.

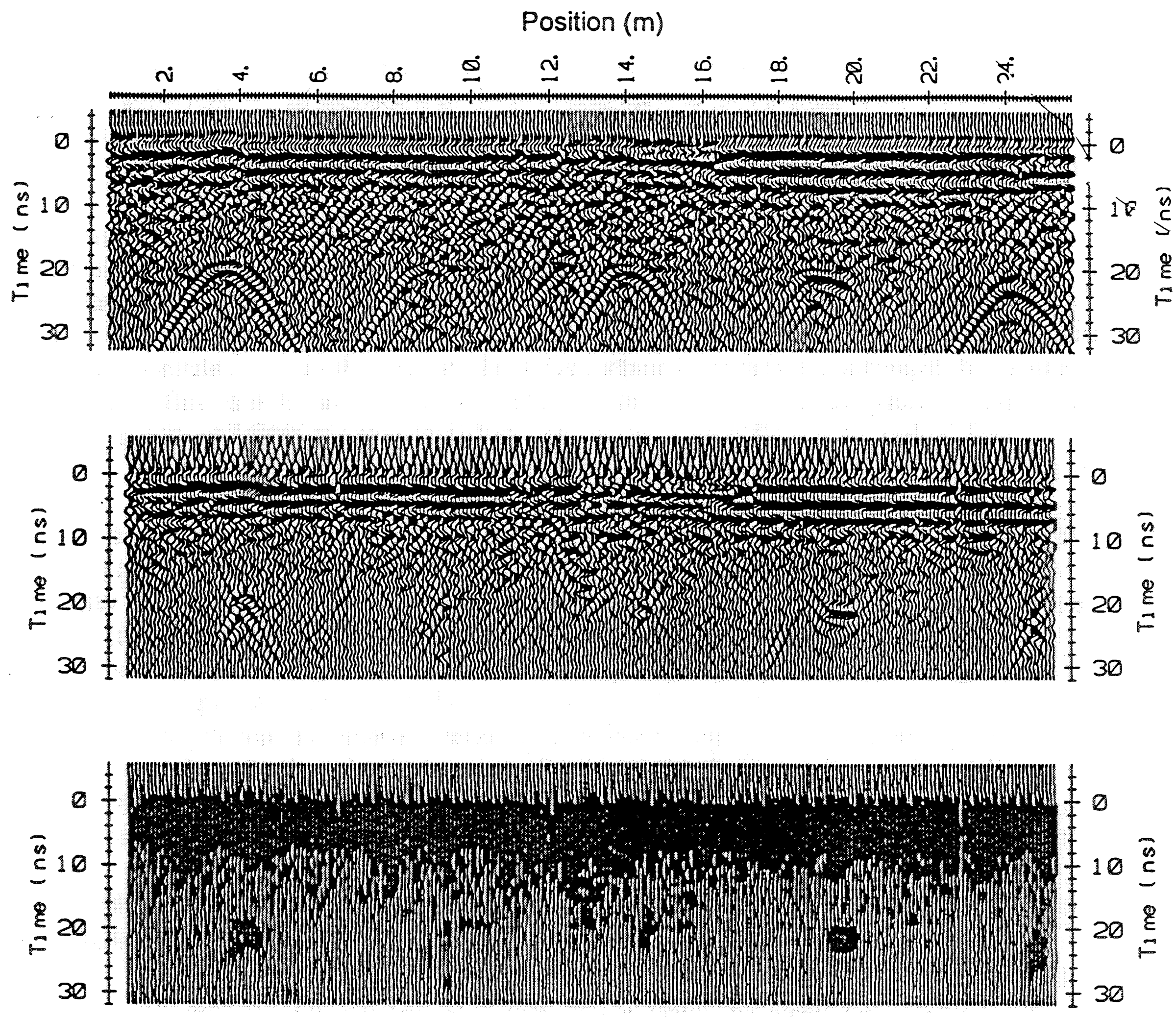


Exhibit 3.2.1.1-12: These data were acquired at a controlled test site of buried pipes and barrels. The targets as well as some zones of disturbed soil yield classic hyperbolic time position responses. Migration is a process by which an image somewhat more similar to the original target geometry is reconstructed. The middle section shows the result of applying F-K migration algorithm assuming a constant background velocity. The bottom section is obtained by computing envelope attributes of the migration section which yields a fuzzy image of the actual target. The small pipes at 9 and 14 meters collapse to very local images. The 0.5 meter pipe diameter at 4 m and the barrels at 19 and 24 m remain extended in space as expected. The migration section provides a more correct representation of the ground. However, to many experienced GPR users, the hyperbolic shapes visible in the original data are often more readily identified. The benefit of having all three data presentations available is optimal for interpretation.

3.2.1.2 System Subcomponents

One task of the current effort is to identify optimum system components for the following phases of the project. The availability of all system components is discussed in detail in Appendix III. It shows that all hardware (antennas, receiver, pulse generator, waveform generator, signal processor) needed for the USP radar for use at the MSFC site are available except for certain adaptation of available hardware.

In the following, it is assumed that sufficient energy per pulse is available and does not impact the choice of a suitable set of antennas. However, if more energy per transmitted monocycle is required, then the dispersive characteristics of an antenna with a large time-bandwidth product (*e.g,* > 3,000) can be used to achieve pulse compression. In this way, much greater energy per monocycle, or peak power, can be radiated. Advantage can also be taken of dispersion on receive. A major overall advantage of dispersive antennas is that they are more efficient than nondispersive. However, in the following it is assumed that sufficient energy per monocycle, or peak power, is available on transmit, and sufficient receiver sampling rate is available on receive, so antenna dispersion will be treated as an undesirable characteristic.

Separate transmit and receive, orthogonally polarized antennas are recommended to prevent coupling on transmittance and to gate out the ground reflectance if it is so desired. Another reason is that due to dispersion by the medium and dispersion and modulation by the target, the returning signal may have very different characteristics on receive than it had when transmitted. (The interface between air and soil does not produce the phase reversal (polarization reversal) which is present when the scattering is from a metallic surface, due to the relatively medium-to-low permittivity and conductivity of soil. However, some targets, *e.g.*, pipes, have even lower permittivites than soil. Transmit - Receive (T-R) receive switches are not, in general, practical for antenna isolation due to the slowness of switching time). Bow-tie antennas have been used, but have "ringing" or "ring down" which distorts the transmitted signal. The antennas must be broadband, if they are resonant antennas, and this family includes the nondispersive TEM horn antennas and the bow-tie antenna.

The footprint size of the antenna becomes ever more important as platforms are considered which are at a distance from the ground surface, *e.g.*, as in air operation. The footprint size is reduced for larger distances and for highly attenuating surfaces. Although there is a reduction in beamwidth, there is, of course, no increase in gain. However, the major advantage is that there is an increase in horizontal resolution between targets at equivalent depths.

Antennas:

Due to the linear phase characteristics, short impulse response, 3 db beamwidths of approximately ±250, as well as its proven use in GPR Systems, the TEM horn antenna (Iizuka, 1967; Wohlers, 1970; Daniels, 1980; Pittman et al, 1982; Evans & Kong, 1983; Theodorou et al, 1981; Oswald, 1988) will be adopted for air platform use. In the case of ground platform use, this antenna is both bulky and susceptible to the formation of standing surface return wave capture. Therefore, for ground platform use, dipole antennas will be best.

Source Technologies:

Several high-power short pulse source technologies are under development. For example, besides air-gap sources, and hydrogen pressurized switches, there are the light-activated semiconductor switches, in which the semiconductor can be silicon, GaAs, diamond and silicon carbide. All these need to be laser-activated and all, except, perhaps for silicon-based, have reliability, duty cycle, yield, filament creation or jitter problems. Furthermore, light-activated switches are certainly not needed in the Phase II work. As the range of pulse durations of interest is in the 100's picosecs to, at most 1 - 5 nanoseconds, and fast offset, avalanche transistors can provide the required peak powers of a few watts. For programmable crafted waveshape source technologies, linear light-activated silicon switches are the candidates.

Waveform Design:

A variety of signal types have been used: AM, FMCW, CW, stepped FM, as well as pulse. AM and CW techniques have many disadvantages, the main being that using low frequencies to penetrate lossy ground results in poor resolution. It is also much more difficult to process returning signals when the transmit signal is still operating. The stepped FM technique is a hybrid which requires lengthy processing and must also pay the penalty of drastic reduction in resolution in exchange for deeper penetration with lower frequencies.

We will explore pulse methods with variations in the pulse envelope in order to match the pulse to the medium and target. Airborne Environmental Surveys International has used frequency swept pulses (1 - 5 nanoseconds. in duration). As the advantages of short pulses appear to lie in the rapidity of their onset and offset, rather than in the phasing of the frequencies under the signal envelope, such pulses fall within the purview of the present short pulse program.

Receiver Technologies:

The presence of strong reflections from the ground surface and possible leakage signals from the transmitting to the receiving antenna, as well as relatively weak returning signals necessitate powerful temporary automatic gain control to compress the dynamic range of the input signals. A genuine time-domain receiver is required (cf. Barrett, 1995) which preserves the instantaneous frequencies and phase of the returned signals, and, at the same time, all ringing effects must be removed from the circuitry. The receiver paradigm must be a homodyne (rather than heterodyne) receiver, due to the nonlinearities imposed by a local oscillator, and the resulting loss of information and signal energy. Bulk acousto-optic devices are available which are fast enough (GHz bandwidth) to preserve individual signal fine structure, but in tandem with CCD arrays are also able to respond to up to a μs-length data stream. (generally, only 100 - 200 nanoseconds of data stream is required). The receiver will acquire, amplify and autocorrelate the signal data stream, and then digitize and handover to the processor.

Processor Technologies:

The signal processor functions in two modes: *(1)* the single probe detection mode; and *(2)* the multiple probing imaging mode. In both modes, the velocity of the signal through the layers will be estimated on semiempirical grounds and the hyperbolic migration will be detected and reduced or eliminated. Using GPS P-code positioning data, a 3D subsurface 3D layer can be constructed with features of significance: voids, underground objects, water, etc., highlighted. When ground attenuation permits, synthetic aperture processing methods can be used.

Signal Processing:

The signal processing for GPR, resulting in "user friendly" operation requiring minimum interpretation by experts, is discussed in Appendix III. The basic aspects incorporated in signal processing include *(1)* the use of matched filtering (use of an incident pulse that "mimics" the signal reflected from the target being probed and the media around it, and *(2)* use of a coded pulse train (e.g. a pulse train with known interpulse interval coding) with each pulse of the kind indicated under *(1)* just preceding. Both of these features enable reduction of clutter, improve signal-to-noise ratio, and enhance target feature recognition and discrimination. Use of wavelet analysis is preferred for the treatment of returning signal data streams to remove noise and clutter and preserve the instantaneous signal events. Once the treatment of the returned signals has been accomplished they can be processed to generate maps or presentations in the format desired. For additional details, see Appendix III.

USP Technology Effectiveness:

A summary of the effectiveness of USP RF Sensing technology: is provided below:

Penetration Depth:

Excellent. Depends on soil and soil conditions. The less conductive the soil, the deeper the penetration. *e.g.*, 10's of meters. The technology is limited more by the increased amount of processing required at deeper penetrations, than a lack of power. The advanced approaches detailed here will permit deeper penetration.

Spatial Resolution:

Excellent. Depends on the pulse duration and receiver sampling speed. 1 nanosecond provides 6 inch of resolution; 500 psec., 3 inch; 250 psec. 1.5 inch. Fine structure of a returned pulse can provide even finer resolution capability

Quantitative Accuracy:

Good. The quantitative accuracy depends on differences in dielectric properties which are stable over long time durations.

Equipment modifications required, if any, to meet NASA /MSFC goals:

Essential component technologies are available. Impulse radars have been used in military and source commercial programs. However some modifications will be required to incorporate wave crafting and processing methodology and to adapt the technology to the specific purposes of NASA MSFC. For the CTS, one supplement a Sensor & Software, Inc. pulse EKKO 1000 portable all digital GPR or the AES system to achieve the wave crafting agility needed. The pulse EKKO 1000 consists of six basic components, namely, a pair of identical antennas, a transmitter electronics unit, a receiver electronics unit, a control console and a personal computer. The pulse EKKO center operating frequency is selected by mounting an appropriate resistively damped dipole antenna on the system. **Exhibit 3.2.1.2-1** shows a block diagram with modifications made to the pulse EKKO 1000 system to incorporate a waveform generator and amplifier (Hewlett-Packard 71604B) in place of the pulse EKKO transmitter. This straightforward replacement together with the choice of antenna discussed, permits the required agility in waveform crafting. Data collection and analysis methodology are discussed in Appendix III.

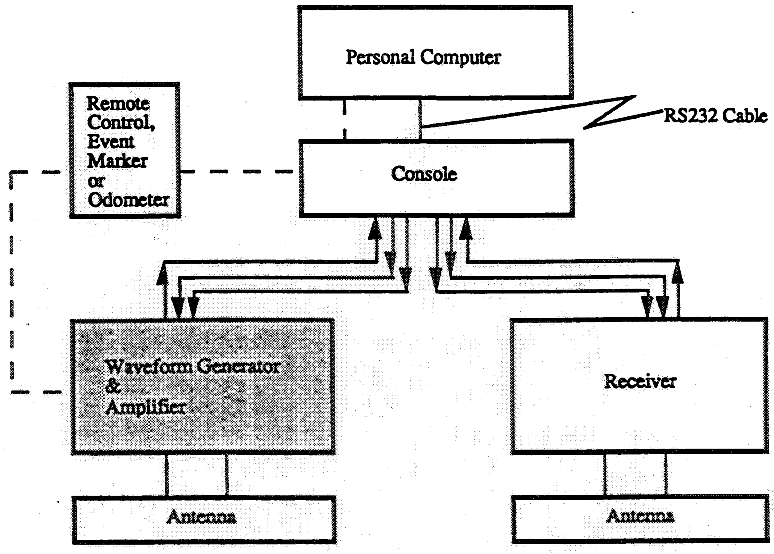


Exhibit 3.2.1.2-1: A block diagram with modifications made to the pulse EKKO 1000 system to incorporate a waveform generator and amplifier (Hewlett-Packard 71604B) in place of the pulse EKKO transmitter.

3.2.2 Shallow Seismic Reflection Profiling

High-resolution, shallow seismic reflection profiling is one of the modalities selected. Similar to GPR which detects changes in electric properties, seismic reflection profiling images abrupt contrasts in acoustic impedance (the product of density and seismic velocity) between lithologic units. These properties are influenced by factors including rock type, fracturing, porosity and degree of water saturation. The image produced by this method is similar to a cross section of the earth along the profile. High-resolution seismic reflection has been used successfully in subsurface mapping of intra-alluvial features (Hill, 1992; Meekes, 1992; Brabham and McDonald, 1992, Davies et al. , 1992; Miller et al., 1990), detection of water table (Birkelo et al., 1987,), mapping bedrock below glacial till (Keiswetter et al., 1994), and in the mapping of glacio-lacustrine and glacial till lithologies (Slaine et al. , 1990). See **Exhibit 3.2.2-1** for an example of shallow seismic data from a fluvial environment.

For the CTS surveys, the CMP geometry of seismic reflection profiling will be used. This method involves the collection of multiple seismic traces with different source-receiver offsets that sample the same subsurface location (**Exhibit 3.2.1-3**). The method generally provides superior signal to noise ratio, high resolution images of the boundaries of rock units, and information about the seismic velocity of the rocks. The resulting images and velocity information will complement detailed lithologic observations obtained from wells, boreholes, and / or outcrop studies and will extend the ability to determine fluid flow parameters in complex environments.

Different acquisition parameters (choice of source and receiver spacing and offset range) are required to optimally image depth ranges of 0 to 20 m, 20 to 100 m, or 100 to 1000 m (Steeples and Miller, 1990), which will be referred to as shallow, medium, and deep penetration respectively. The shallow range is best imaged with a small, high-frequency source and closely spaced receivers. Deeper penetration requires a larger, lower frequency, source (lower frequencies travel further in the ground) and receivers at a larger range of offsets.

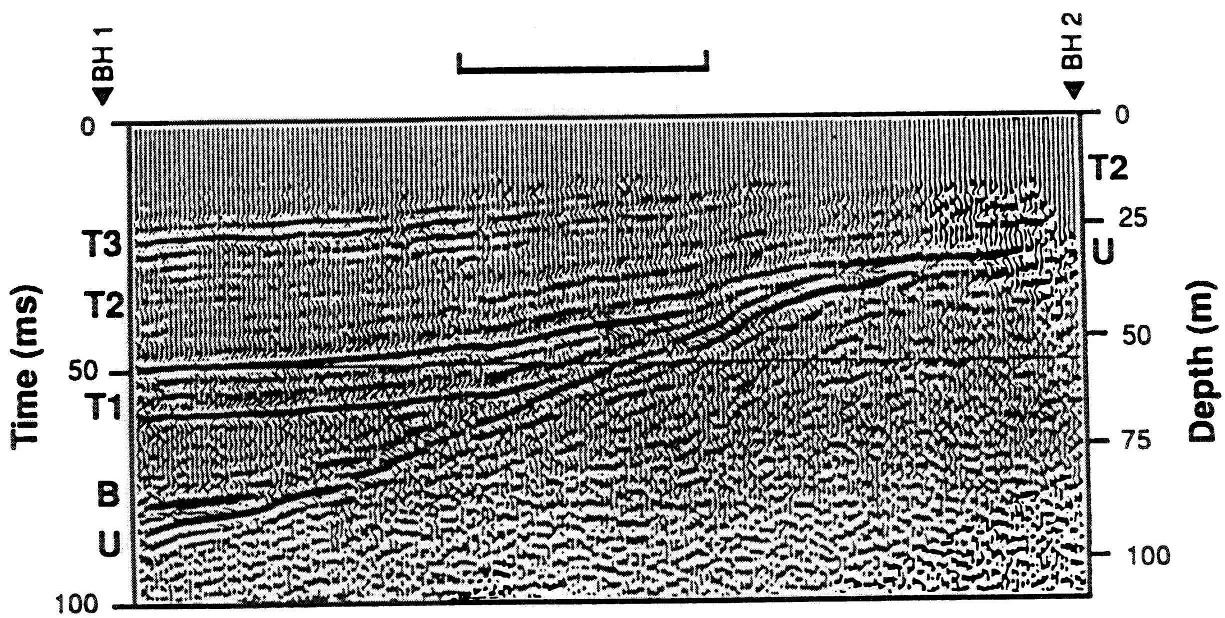


Exhibit 3.2.2-1: Stratigraphy is well-imaged in this high-resolution seismic profile. The profile crosses mudstones that are Mesozic age overlying low-grade metamorphic rocks. From Hill, 1992.

Since target depth may be as great as 100 m and resolution high enough to detect fine scale variations in porosity, it may be necessary to sample increasing depth intervals independently along the same line. This will require multiple passes over the same line with different source and receiver arrays. Large differences in data quality observed between seismic sources will necessitate testing of alternate sources at the MSFC site before acquisition (**Exhibit 3.2.2-2**).

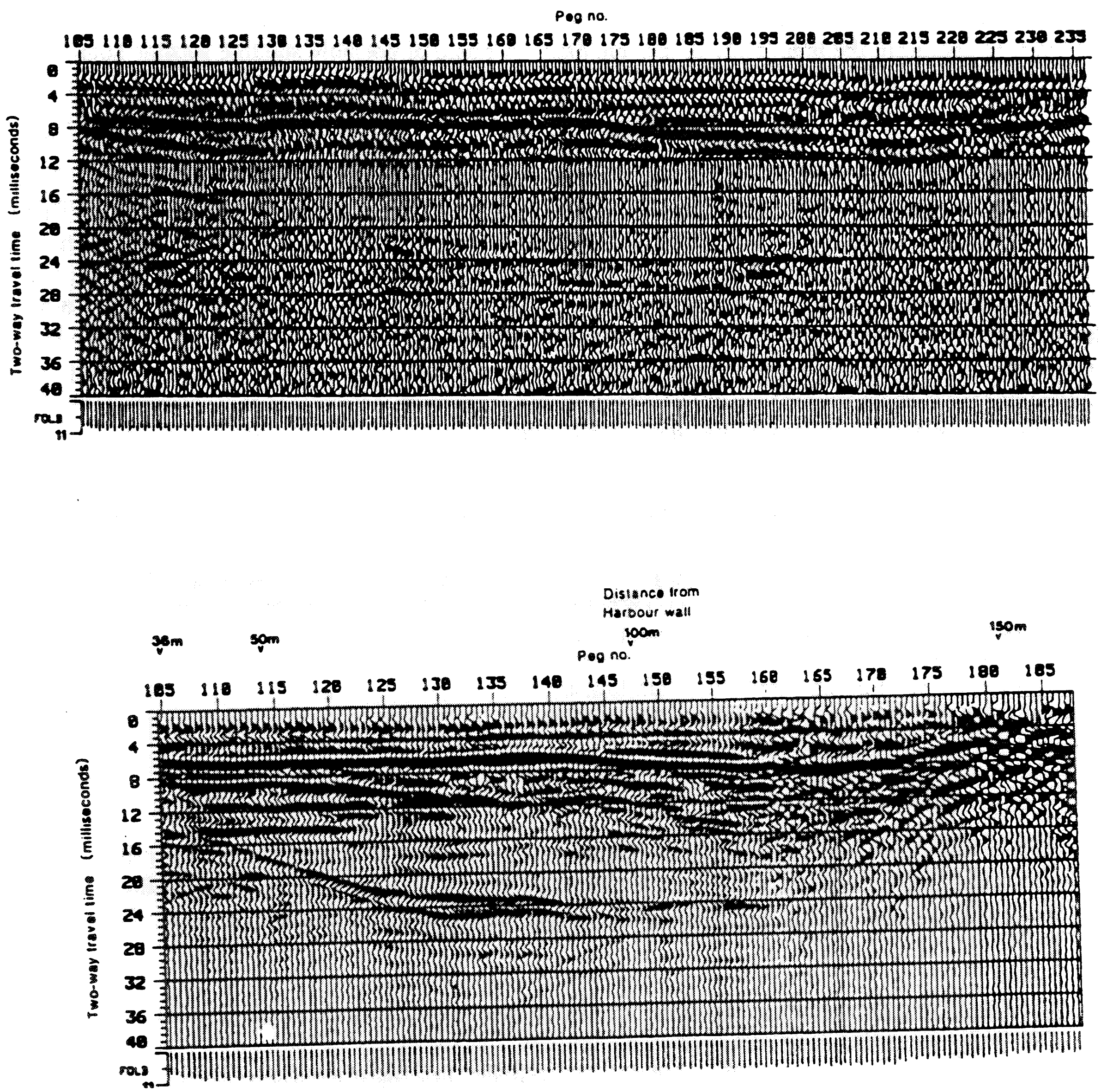


Exhibit 3.2.2-2: A comparison of shallow seismic records using a sledge-hammer source *(top)* and detonator (bottom) clearly demonstrates the superiority in this example of the detonator. The cost differential may, however, prevent widespread utilization of this technique. The detonator source was implemented by driving a spike 0.5 - 1 meter into the ground and placing the detonator in the hole, From Brabbam and McDonald, 1992.

Choice of seismic source and receiver geometry must be determined by performing a "noise test" for any new site before acquiring the main body of seismic data. A range of possibly suitable seismic sources are fired several times each into a linear array (with length equal to the maximum depth of interest) of closely spaced (1/4 to 1/2 m) receivers. The signals are recorded and analyzed to determine which source is of adequate amplitude and has the broadest and highest frequency range when recorded at each offset distance. These data are also used to determine the number and spacing of seismometers needed for each receiver location to attenuate undesirable surface waves. Forty hertz geophones will be used for all land surveys. This should allow for accurate recording of frequencies in the range of 40 - 400 Hz. A 24- bit dynamic range recording system will be sufficient to record all useful energy in this frequency range. Sources to be used, expected dominant frequencies, and estimated resolutions for compressional waves at three depth ranges are listed in **Exhibit 3.2.2-3**. Based on documented lithologic variation and flow model requirements, these resolutions will be adequate for this study. Analyzing the work of Steeples and Miller (1990), Knapp and Steeples (1986), Miller et al. (1986), and Hill (1992), we expect to use single geophone groups for the shallow and medium depths with 1 m and 1 - 2m group spacings, respectively.

Depth Range	Sources	Dominant Frequency	Vertical Resolution	Horizontal Resolution
3 m - 20 m	small caliber rifle, propane igniter	200 Hz	1.25 m	1.75 m
20 m - 100 m	high-powered rifle, buffalo gun (various gauges), sledge hammer & plate	125 Hz	4 m	6 m

Exhibit 3.2.2-3: Resolution estimates were made assuming migrated profiles. (Information based on work by Knapp and Steeples, 1986; Yilmaz, 1987; Miller et al., 1995; Slaine et al., 1990; Hill, 1992; Keiswetter, 1994; Steeples and Miller, 1990; Haeni, 1986)

Large lateral velocity variation, elevation, and weathered layer thickness changes relative to the depth of interest, make detailed static corrections and velocity analysis essential when processing shallow seismic reflection data (Steeples and Miller, 1990). A complex lithologic environment only exaggerates these problems. An analysis known as surface-consistent statics corrections is used to take out geologically-related variations in travel time. A surface-consistent statics correction algorithm works by analyzing the arrival times of reflections. If all of the reflections on every trace recorded at a given position arrive later than those at other positions, it is likely that the late arrival is due to a slower near-surface velocity at that location and thus has a geologic meaning. Thus, by analyzing the consistency of the arrival time in relation to their surface position, geologically-related shifts in travel time that greatly degrade the quality of seismic data are removed. Statics corrections are one of the most important corrections made in shallow seismic data processing.

All data will be processed using standard CMP processing techniques including migration (to accurately image sharp lateral variations and steeply dipping reflectors). Basic filtering and display will be completed in the field, on the day of acquisition using a lap top computer and DOS based software, to allow rapid and efficient adjustment of acquisition parameters.

Although site-specific variables such as the vegetative cover and water cover will significantly affect the acquisition rate, we estimate that 3 people can acquire 300 shot points per day for the shallow / medium and deep intervals (Steeples and Miller, 1990).

Few comparisons of shallow seismic and GPR surveys are available, and these use seismic refraction rather than reflection methods (Benson, 1992; Carpenter et al., 1993). However, Young et al. (1995), in a comparison of several geophysical methods including GPR and refraction seismic, state that the seismic and electrical properties appear to change at the same boundaries. The boundaries corresponded to facies changes in wells in the survey area. Such results are encouraging for the proposed surveys at the MSFC.

The technology for shallow seismic surveying is based on low-cost, portable data recording units coupled with geophone strings. These technologies are readily available and there are a number of companies from which to choose. The sources used in shallow seismic surveying are the most variable. Sources range from commercially produced impact sources with a fairly low frequency range to more innovative devices. Researchers have used rifle and shotgun blasts, jackhammers, and buried detonators. Also used are hammer and plate sources, but these produce a lower frequency signal than is appropriate here. All of these sources are readily available. Testing at the CTS will be necessary to determine which source produces the resolution and penetration needed for the survey area.

For the targets and target depths of the MSFC area, it is probable that lightweight jackhammers, small caliber rifle, and small detonators will produce the best results.

3.2.3 Neutron Imaging Technique Description and Application to the MSFC Survey

The Neutron Imaging technique specifically addresses the goal of "in situ" chemical plume detection and mapping. The technique uses the interaction of neutrons with the atomic elements of the soil, and provides information on the chemical composition of the near ground surface without having to take samples. Its one considerable advantage is that the analysis can be virtually performed onsite. Physically, as a result of the interactions of the neutrons with the soil elements, gamma-ray photons of specific energies are emitted. The energies of the gamma-rays are then used to detect the presence of specific elements. The technique has been, in particular, successful for the detection of heavy metals such as lead or mercury and organic compounds containing chlorine such as TCE or PCB's. For the past 20 to 30 years, Neutron Imaging has been used for oil well logging and geological surveys. Its use has been recently expanded to environmental surveys and food analysis. For environmental surveys, the key technologies, including neutron sources, detectors, and data processing, is mature and commercially available. In particular, computational and experimental simulations of the complex spectra acquired during such measurements will ensure a prompt and efficient analysis of the data during onsite measurements at the CTS / MSFC. The tool will be assembled and tested at the HARC which has significant experience in developing and applying the technology to the downhole environment for oil companies.

3.2.3.1 Principles of Neutron Imaging

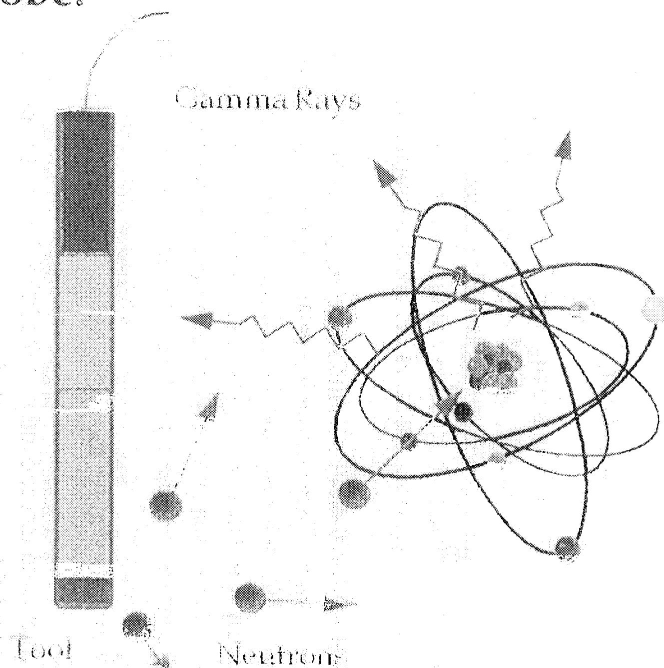
The principle of Neutron Imaging is illustrated in **Exhibit 3.2.3.1-1**. A neutron imaging probe is composed of a neutron source, a high resolution gamma ray detector, an electronics and data processing package, and a cooling system for the detector. The neutron source emits neutrons within the formation where they interact with individual atoms. The neutron-nucleus interaction results in the production of gamma ray photon(s) of specific energy(ies). The energy of the photon is determined by the particular nuclear reaction taking place.

Neutron Imaging Principle

Goal: detect the presence of elemental compounds in the formation surrounding the probe.

Principle:

- A neutron source emits neutrons into the formation.
- The neutrons interact with individual atoms within the formation.
- Gamma rays are emitted as a result of the interactions.
- A high resolution gamma ray detector collects some of the gamma rays and information is extracted from the energy spectrum.



ECG - Houston Advanced Research Center (TDL)

Exhibit 3.2.3.1-1: Schematic illustrating the principle of neutron imaging. A neutron source emits neutrons into the surrounding formation - the neutrons interact with the nucleus of the atoms of the formation - characteristic gamma rays are emitted as a result of the nuclear reaction - a high resolution detector measures the energy of the gamma rays - from the resulting energy spectrum information is obtained as to the composition of the surrounding formation.

These reactions can be grouped in three different categories: *(1)* inelastic gamma rays are emitted as neutrons collide with nuclides while slowing down in the formation; *(2)* capture gamma rays are emitted when neutrons are absorbed by nuclides; and *(3)* activation gamma rays are emitted as nuclides release part or all the added energy acquired when they absorbed a neutron (delayed reaction). While gamma rays emitted as a result of the first two processes are emitted almost immediately up to a few milliseconds, the third type of gamma rays are emitted with a delay depending upon their particular reaction. This distinction is important only if a pulsed system is used and the spectra are recorded at given time interval. For this survey, the spectra will be acquired while operating the neutron generator and for a period of time necessary to obtain good statistical data.

The second type of particles involved in the Neutron Imaging technique are the gamma ray photons generated during the nuclear reactions. They carry the information as to which elements are in the probed formation. But for this information to be recorded, the gamma ray detector must record the full energy of the photon. Two factors lead to the loss of the information. First, the detector itself must register as accurately as possible the total energy of the incident photon. A high efficiency, high resolution detector is therefore selected (large volume high purity germanium detector). The second cause for the loss of information is linked to the photons travel in the formation. While traveling through a material, photons undergo interactions which lead to the absorption of the photon or the loss of energy. If a photon loses part of its energy, the information as to the initial nuclear reaction and therefore the source element is lost. It is therefore only the uncollided photons that carry the information as to the composition of the surrounding formation. To register this information, the detector must be sufficiently close to the initial reactions to record enough uncollided photons. The uncollided photon mean free path is therefore an important factor for the survey set-up. Computations of the ranges of both neutrons and photons are presented later.

To identify the presence of a particular element in the formation, one looks for the presence in the gamma ray spectrum of an energy line corresponding to a nuclear reaction involving the element. **Exhibit 3.2.3.1-2** displays a gamma ray spectrum taken at HARC for a naturally radioactive soil sample. The sample has not been activated by neutrons but contains potassium, uranium, and thorium which are all naturally radioactive. Some of the energy lines are identified by indicating both the energy of the line and the source element. For an irradiated soil sample, there are a number of different elements and for each element there are often several nuclear reactions involved. The detector itself and the other structural elements of the probe can also contribute to the overall spectrum. **Exhibit 3.2.3.1-3** illustrates an example of a spectrum showing both the influence of the detector housing and the formation. The raw spectra analysis is streamlined if the elements of interest have been identified and if computational simulations and laboratory experiments have been previously performed. For the computational simulations, the code MCNP can be used to simulate energy spectra.

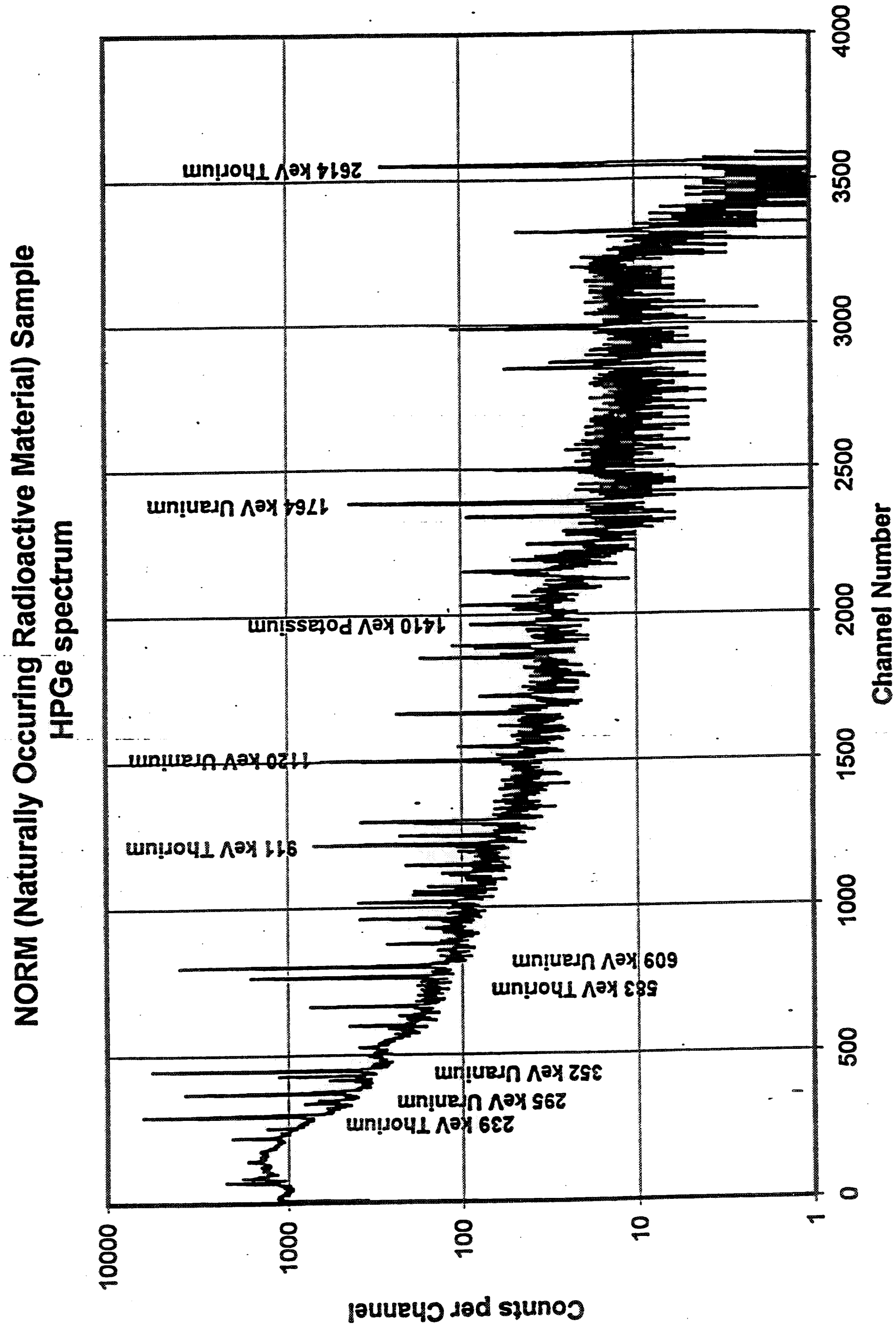


Exhibit 3.2.3.1-2: High purity Germanium Spectrum of a soil sample containing naturally occurring radioactive materials (Uranium, Thorium and Potassium). The different energy peaks are the result of specific nuclear reactions which allow for the identification of the source of the peak (atomic element). The intensities of the peaks are related to the respective concentrations of the elements in the soil sample.

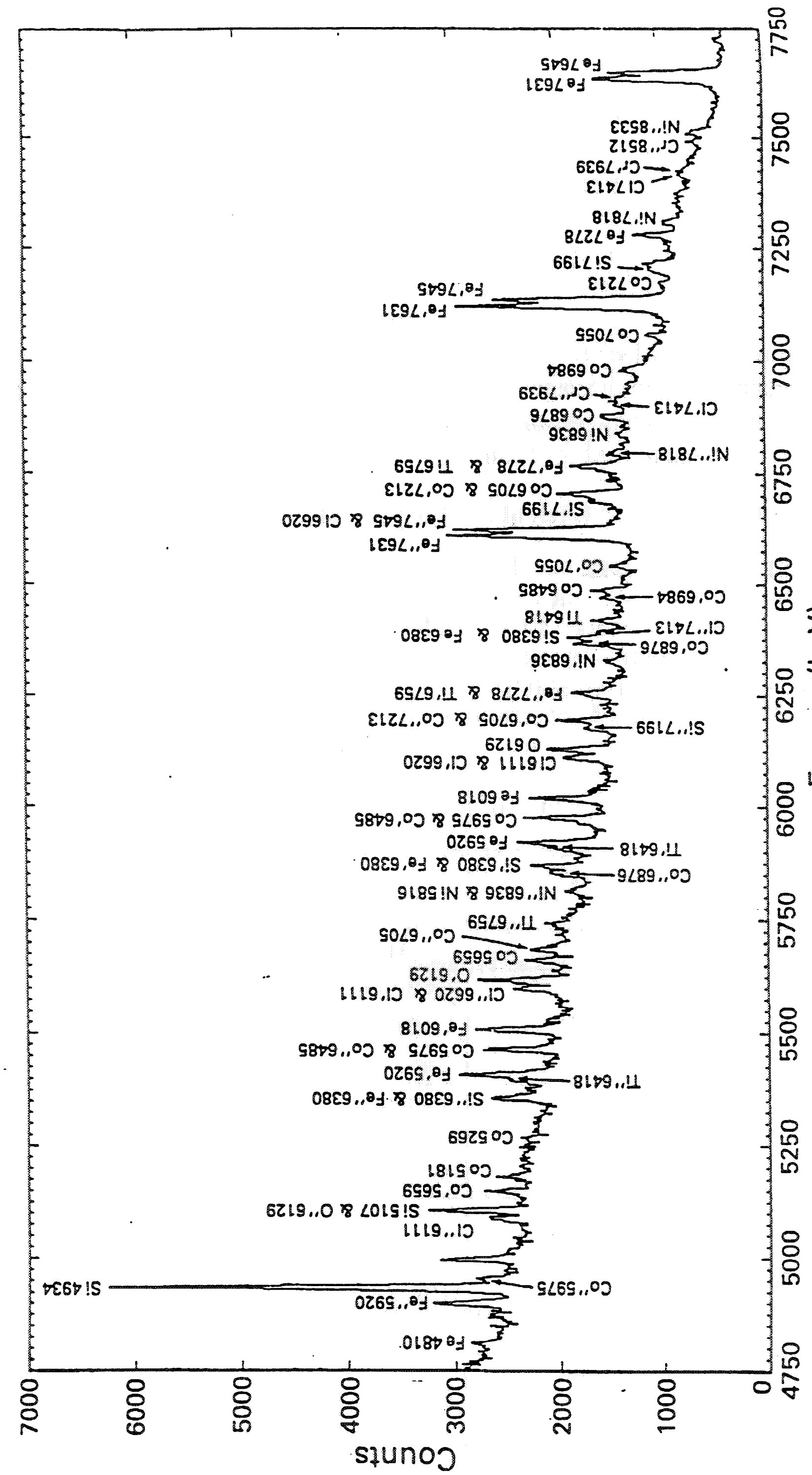


Exhibit 3.2.3.1-3: Capture gamma ray spectrum showing gamma rays from the detector housing in addition from the rock elements. Figure extracted from "Review of Nuclear Techniques in Subsurface Geology" by J.S. Schweitzer and D.V. Ellis in IEEE Transactions on Nuclear Science, Vol. 35, No.1, 1988. The Ni, Co, and Cr peaks are from the cryostat while Fe, Ti and Si are from rock.

3.2.3.2 Review of Relevant Neutron Imaging Techniques

Neutron Imaging has been used in various forms since the early 1960s for oil well logging. The technique was initially used to acquire general information such as porosity by measuring the neutron transport properties of the formation. The use of a neutron source to irradiate the formation and a gamma ray detector to allow for the detection of individual elements in the formation started in the late seventies and early eighties in the petroleum industry. The U.S. Geological Survey Bureau used the method to characterize rock formations and the quality of coal deposits. More recently, the technique has been expanded to fields such as food analysis and biological sample analysis as well as environmental characterization. For environmental surveys, the technology is mature, the hardware used is in its early stages in terms of the previous work. However, since the basics of the technology are the same as for the more mature applications, the adaptive steps are not seen as a problem. The technology promises to be clearly successful and have a significant impact on environmental surveys in the immediate future.

3.2.3.3 Suitable Interactions for Each of the Identified Chemicals

Each element in the formation can be identified by a particular nuclear reaction taking place between an incident neutron and the nucleus of the element. Each nuclear reaction results in the release of gamma ray(s) of particular energy(ies). The selection of a particular energy line is based on potential interferences from other elements and based on the relative probability of gamma ray emission (related to the reaction cross section). An ideal line has no potential interfering lines and generates a strong signal for a given elemental concentration in the formation. The chemicals of concern to the MSFC were grouped by element and a specific energy line was identified for each of these elements. The energy lines were selected from lines previously used and reported in the literature and for which no interferences were recorded. Other lines could be selected if an unforeseen interference was to complicate the measurements.

Types of Chemical	Gamma Ray Line	Chemicals of Concern
Metals		
Aluminum (Al)	1.78 MeV[1,2]	Aluminum
Cadmium (Cd)	0.59 MeV[2]	Cadmium
Chromium (Cr)	8.88 MeV[1]	Chromium
Copper (Cu)	1.04 MeV[2]	Copper
Lead (Pb)	7.37 MeV[2]	Lead
Nickel (Ni)	9.00 MeV[1,2]	Nickel
Silver (Ag)	0.66 MeV[2]	Silver
Zinc (Zn)	7.86 MeV[2]	Zinc
Other elements		
Boron (B)	0.48 MeV[1,4]	Boron oxides
Chlorine (Cl)	6.6 MeV[2,3]	TCE ($CHClCCl_2$) - Chloroform ($CHCl_3$) - Perchloroethylene ($(CCl_2)_2$) - DDT ($(ClC_6H_4)_2CH(CCl_3)$) - HCl - Mustard Gas ($(ClCH_2CH_2)_2S$)
Fluorine (F)	to be determined	Hydrofluoric acid (HF)
Nitrogen (N)	5.27 MeV[2]	Cyanide (CN^-)
Phosphorous (P)	to be determined	Phosphorous
Sulfur (S)	2.38 MeV[2]	SO

Exhibit 3.2.3.3-1: Gamma Ray Energy Lines of Selected Chemicals from the MSFC and CTS

As can be seen from **Exhibit 3.2.3.3-1**, the analysis for the metals will be simple as the elements will be detected directly. For the other elements and chlorine in particular, the detected element will potentially be related to several chemicals. A different type of analysis would have to be performed to confirm the exact nature of the chemical. This is however not a serious concern as the major goal of the survey is to locate and map areas where the presence of some of the elements is recorded. The exact determination of the nature of the chlorine based chemical can be left for a more localized survey. The following chemicals were not included in the list: Benzo(a)pyrene ($C_{20}H_{12}$) - Benzene (C_6H_6) - Xylene ($(CH_3)_2C_6H_4$). Their atomic composition is based on materials that are also found in the soil and therefore only unusually large quantities would be detected. These chemicals have all the particularity of being light volatile organic compound. If the penetrometer technology is selected, it would be relatively simple to integrate a detection system targeted towards light volatile chemicals such pyrolysis or a combination of a sniffer and a small mass spectrometer. Beryllium was not included in the list and will probably not be detected by this technique.

3.2.3.4 Choice of the Neutron Source(s)

Two general types of neutron sources are readily available for Neutron Imaging: chemical sources and accelerator based sources. Chemical sources are usually based on a mixture of an α-emitter such as Americium or Plutonium and Beryllium: AmBe and PuBe. These sources emit neutrons within a broad energy spectrum up to about 12 MeV with the largest fraction of the neutrons emitted between 2 and 6 MeV. The accelerator tubes accelerate deuterium ions into a target containing deuterium (D-D source) or Tritium (D-T source). The D-D sources produce 2.45 MeV neutrons while the D-T sources produce 14.1 MeV neutrons. The energy of the neutrons will mainly affect two parameters: the type of inelastic interaction taking and the range of the neutrons in the formation. The first parameter is not critical for this survey since inelastic scattering will not be one of the major interaction modes used. The second parameter is neutron mean free path into the formation and is of significant importance for the surface measurements. The larger the area covered by the emitted neutrons, the larger the area sampled at one time as the gamma ray detector can be moved around while keeping the neutron source and the electronics in place. Accelerator sources also have the significant advantage to emit neutrons only when activated and are therefore easier to transport and handle. A 14.1 D-T accelerator source is selected for this project.

3.2.3.5 Initial Calibration and Testing Protocol

To conduct the survey, a modular probe which allows a quick conversion from a surface measurement to a well measurement configuration will be assembled. The probe itself will have to be tested including the neutron source, the gamma-ray detector, and the electronics and data acquisition package. This testing can be done first in the laboratory on soil samples taken on the MSFC site. Also, before taking measurements in the field, it is desirable to test the tool in a test hole of calibrated formations surrounding a borehole. Such testing will not only allow testing of the equipment and the procedures but will also provide an opportunity to analyze and compare the results for a series of known formations. Another result that must be obtained from the testing of the tool is a typical spectrum resulting from the interaction of the neutrons and the tool structure.

Limitations of Neutron Imaging:

One question is the investigative range of the technique. The range of the Neutron Imaging can be both a considerable advantage if compared to the usual chemical analysis techniques or a limitation if compared to the range of seismic or EM type measurements. The neutron range varies between a couple of feet for hydrogen rich soils to up to 10 to 12 feet for dry terrains. The photon ranges are in general around a couple of feet and increase when there is no high- Z materials in the formation. The ranges of photons and neutrons in the modeled MSFC soil were simulated by using the Monte Carlo Code MCNP developed at Los Alamos National Laboratory (Ref. 1). The MCNP simulations for neutron ranges in the CTS soil for 14 MeV neutrons are displayed in **Exhibit 3.2.3.5-1** The measurement range selection results from a trade off between the neutron flux and the measurement time. A neutron range up to 80 to 90 cm can be used as a reference for initial estimates. For longer counting times, the neutron flux could be sufficient at distances up to 200 to 250 cm. For surface surveys, it might become more cost efficient to move the neutron source more often and reduce the counting time by not trying to extend to larger distance between source and detector. For a large scale survey, the source and detector can be mounted on a vehicle and the source and detector will be relatively close to each other. The advantage would be the higher output (area / time surveyed).

The range of the photons is important for the evaluation of the range of the technique. The result of MCNP simulations of photon ranges in the CTS soil for 6.6 MeV photons (chlorine) is displayed in **Exhibit 3.2.3.5-2.** The 6.6 MeV chlorine line was chosen because of its importance for the detection of several of the chemicals of concern. The measurement range then becomes the sum of the neutron range and the photon range, about 40 to 60 cm. The detector can therefore be moved up to about 120 to 150 cm from the source. These ranges also depend on the water content of the soil and its exact composition, and can also be somewhat extended for specific applications where the range is at a premium by extending the counting time and / or using a higher intensity source.

Elemental Characterization:

The Neutron Imaging technique allows the detection of individual elements. This can be seen as an advantage and is listed in the attributes of Neutron Imaging. This is also a limitation for chemicals that contain only elements that are already part of the soil composition or for a series of chemicals that share the same elemental composition. In the case of a chemical composed of elements present in the soil matrix, the chemicals can be detected only if an additional impurity is part of the chemical composition. For the case of chemicals sharing the same elemental composition such as chlorine based organics, other characterization techniques must be used in conjunction with the Neutron Imaging unless different impurities can be found to be part of the chemicals. It is worth mentioning that even if the Neutron Imaging technique does not distinguish between chemicals of the same elemental composition, the technique still indicates the presence of their common element. The complementary chemical characterization technique can then be used for only the identified area.

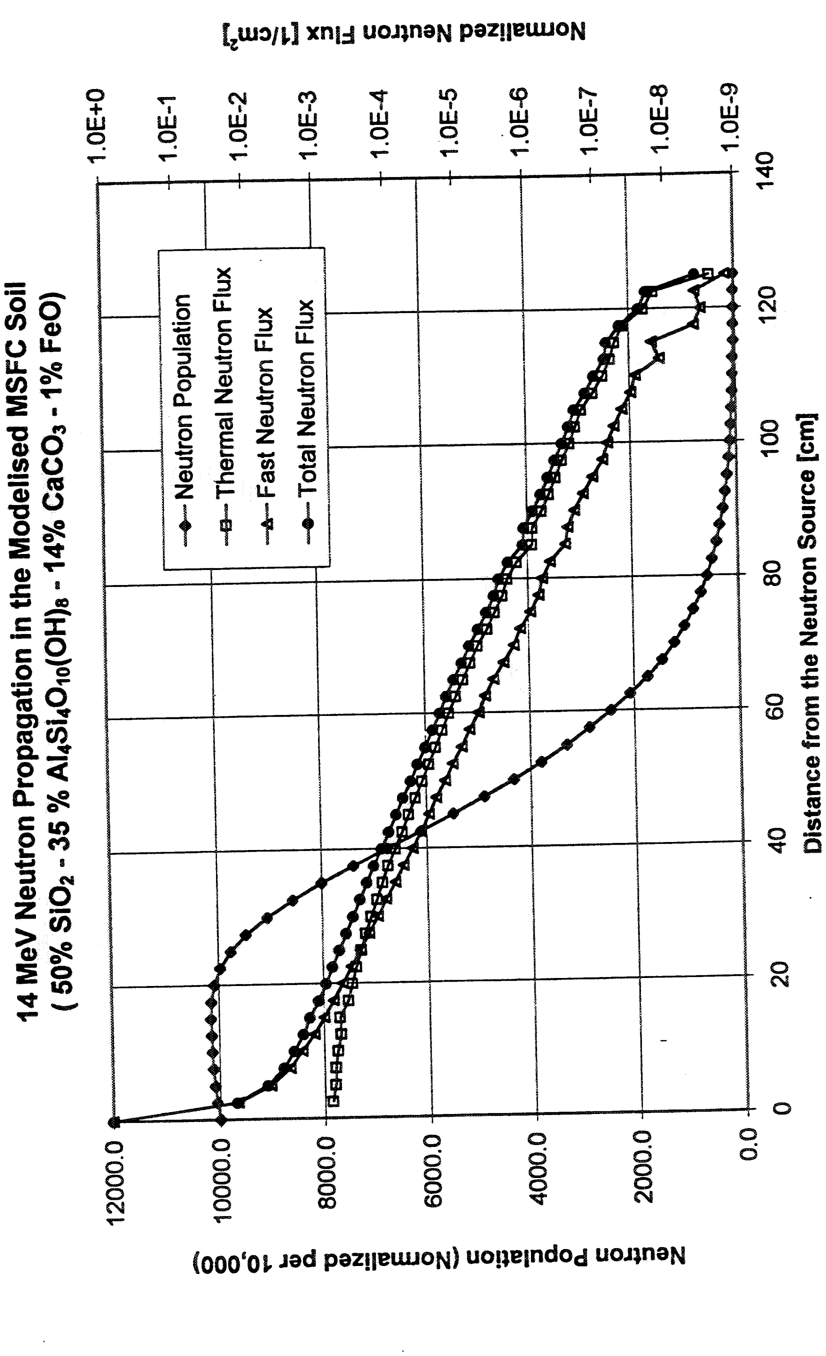


Figure N4. MCNP4a simulation of the propagation of 14 MeV neutrons in a modelized soil similar to the one found on the MSFC beta site. The problem was set as a poiint source surrounded by spherical shells. The neutron population is the population in each shell and the flux is the scalar flux at the boundary between each spherical shells.

Exhibit 3.2.3.5-1: MCNP4a simulation of the propagation of 14 MeV neutrons in a modelized soil similar to the one found on the MSFC CTS. The problem was set as a point source surrounded by spherical shells. The neutron population is the population in each shell and the flux is the scalar flux at the boundary between each of the spherical shells.

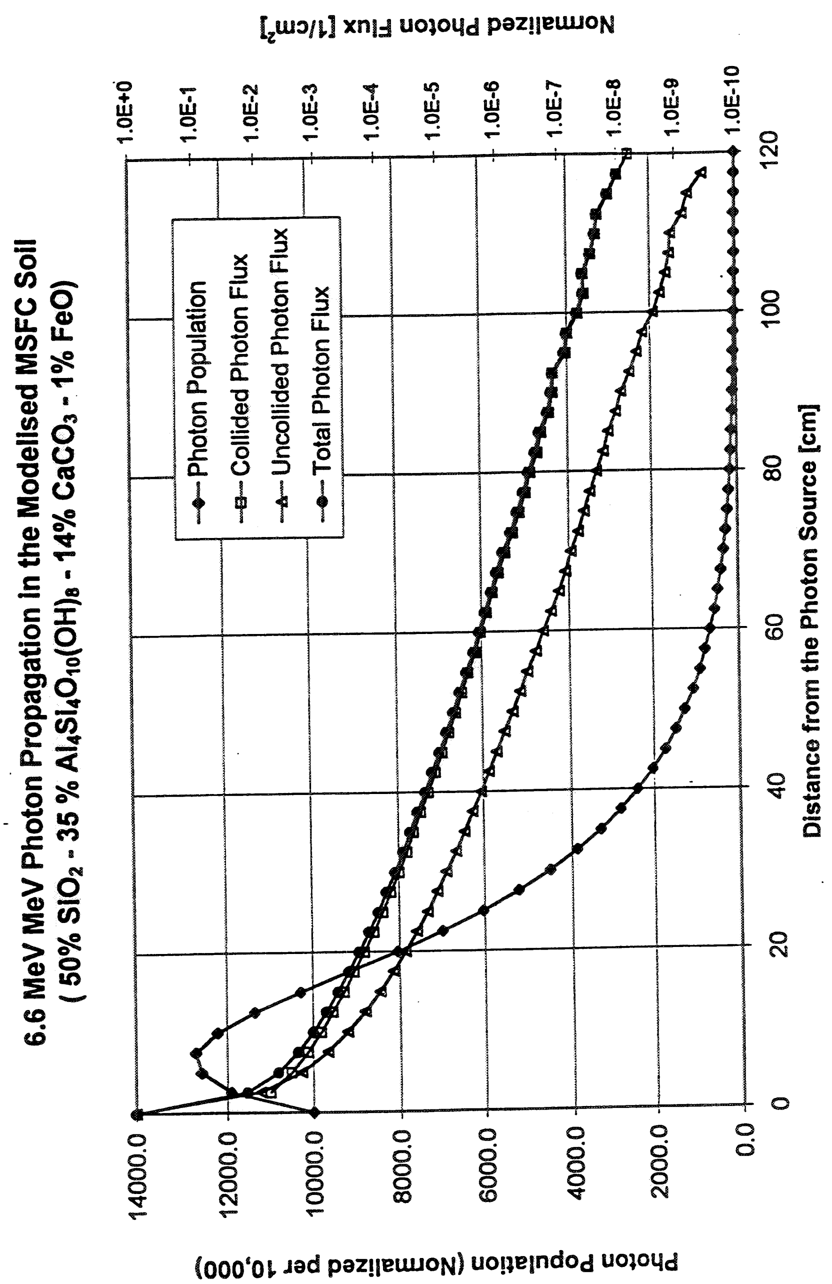


Figure N5. MCNP4a simulation of the propagation of 6.6 MeV photons in a modelized soil similar to the one found on the MSFC beta site. The problem was set as a poiint source surrounded by spherical shells. The photon population is the population in each shell and the flux is the scalar flux at the boundary between each spherical shells.

Exhibit 3.2.3.5-2: MCNP4a simulation of the propagation of 6.6 MeV photons in a modelized soil similar to the one found on the MSFC CTS. The problem was set as a point source surrounded by spherical shells. The photon population is the population in each shell and the flux is the scalar flux at the boundary between each of the spherical shells.

3.2.3.6 Attributes of Neutron Imaging

Elemental Characterization:

A significant advantage of this technique is that most of the elemental compounds of a soil including the potential pollutants, can be detected individually and in-situ by the same technique. Most of the other chemical characterization techniques identify the presence of a particular element only indirectly and several different techniques must be used to perform a broad scan survey. Also, sophisticated chemical characterizations must usually be performed in the laboratory environment, requiring extraction and transport of the soil samples.

In-Situ Measurements:

For most chemical characterization techniques, a survey is conducted in two steps: samples are extracted in the field and then transported to a laboratory for experiments. For the Neutron Imaging technique, an automated data acquisition system can identify the presence of the chemicals of concern. The presence of a chemical in the soil can therefore be immediately detected and if needed additional more sensitive measurements performed. The flexibility of in-situ measurements and analysis are one of the more significant advantages of the technique.

High Sensitivity:

The sensitivity of the Neutron Imaging technique will vary for each element. The sensitivity depends in particular on the probability that a neutron will interact with the particular element (reaction cross section) and the probability that the gamma ray of interest will be emitted during or following the interactions. Minimum detection concentration in the parts per million are to be expected. For elements for which experiments were conducted yielded the following minimum detectable concentrations: Chlorine (1.16 MeV line) 86 ppm, Mercury (0.368 keV line) 33 ppm, Cadmium (0.559 MeV line) 1.4 ppm.

Volumetric Averaging:

For a drill and sample technique, only the drilled core is available for analysis. The volume sampled is therefore relatively limited. As simulated in the previous section, a volume of about four cubic feet is sampled for the MSFC type terrain. Also, there is a strong possibility with the drilling and sampling technique for contamination of the sample. For in-situ neutron imaging, the measurement is made on-site without extraction and transport of the sample. If a casing is involved or if the measurements are made in a well with a particular structure, the interference from the structure can be measured or simulated computationally and taken into account in the analysis.

Through-casing Measurements:

One of the attractive features of the Neutron Imaging technique is its ability to be performed through structures such as the casing of a well or the metal wall of a penetrometer. The neutrons and gamma rays penetrate steel and other metals, the technique can therefore be applied without direct physical contact with the formation. Existing wells, for example, can be used without any further modifications provided that their diameter is sufficient for the tool (> 3½"). The structural composition of the well or penetrometer will influence the overall recorded spectra by somewhat reducing the formation volume sampled (now partly occupied by the well or penetrometer structure) and by adding energy lines corresponding to the structural materials. These lines however should not interfere significantly with the lines selected to measure the presence of the chemicals of concern.

3.2.3.7 Logistics of Operations

Non Invasive Measurements (Surface):

For this type of measurements, only the near ground surface (about 2 ft.) is sampled. For most of the pollutants that penetrate into the ground, sufficient traces should be left in the upper ground surface to be detected by the Neutron Imaging. Also, if the pollutants are periodically brought to the surface by rising ground waters, detectable traces could be left in the near surface. This would be in particular useful for isolated underground pools that keep significant concentrations of pollutants trapped. If such features could be identified, the remediation action would be simpler and more efficient. A schematic of the set-up for the surface measurements is presented in **Exhibit 3.2.3.7-1** The source is placed at a predetermined location and a hollow drum filled with water is placed around the source to protect the crew. The gamma ray detector is moved at different locations around the source. The neutron source is activated only during the measurements. A spectra is collected for each of the locations. The success of the technique will be determined by its ability to measure surface pollutants and by its ability to predict, from the near surface traces, the presence of chemicals deeper in the soil. If the technique is successful, a vehicle containing the source and the detectors could be designed for phase III and a continuous measurement type survey could be conducted.

Semi-invasive Measurements (Cone Penetrometer):

The surface technique is limited by its investigative depth of about 2 feet. For this reason, the Neutron Imaging technique is mostly used in the context of well logging. The neutron imaging technique will be tested in the compatible existing wells (well 28d of the CTS). However the number of available wells is limited and setting up sampling wells for a large area is expensive. However, a cone penetrometer in which a large metallic cone followed by a hollow casing is rammed into the ground can be readily used, and is substantially lower in cost and faster than setting up wells. Yields of up to 12 to 15 cone penetrometers per day should be achievable.

The survey geometry for the well type measurements is illustrated in **Exhibit 3.2.3.7-2.** The probe is lowered progressively into the well and spectra are acquired at regular intervals. The measurements will provide a picture of the underground volume surrounding the well or cone penetrometer. The measurements will also be correlated with the surface measurements to assess the ability of the surface measurements to predict the pollutant content of deeper levels of the soil. Besides well 28d, 4 other areas are selected for well type measurements within the CTS.

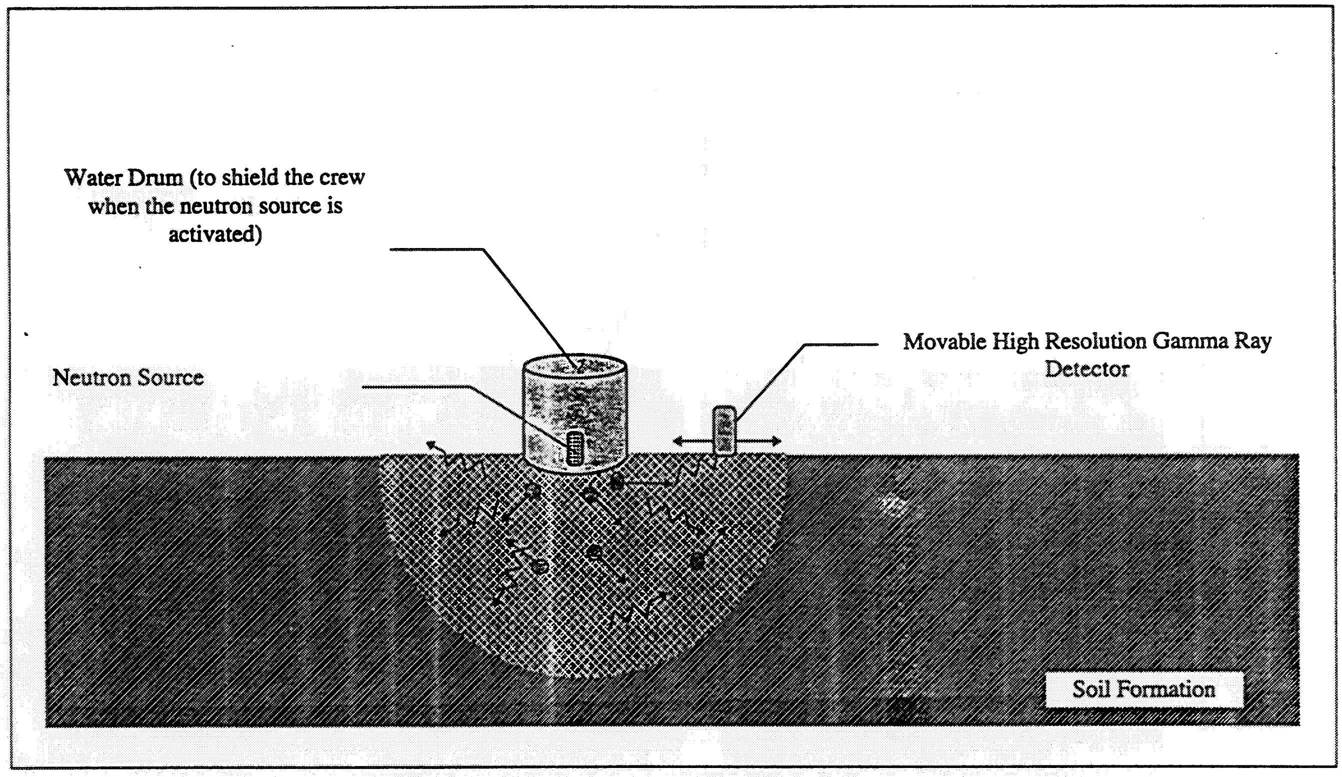


Exhibit 3.2.3.7-1: Schematic illustrating the deployment of a neutron induced gamma ray probe as devised for the survey of the MSFC CTS - Deployment for surface measurements. A neutron source emits neutrons into the soil, the neutrons interact with individual atoms in the formation and Gamma rays are emitted. A high resolution gamma ray detector is moved around the irradiated area and spectra are recorded. A Truck is required to transport the equipment and a vehicle must also be used to move the large water drum used to shield the neutron source.

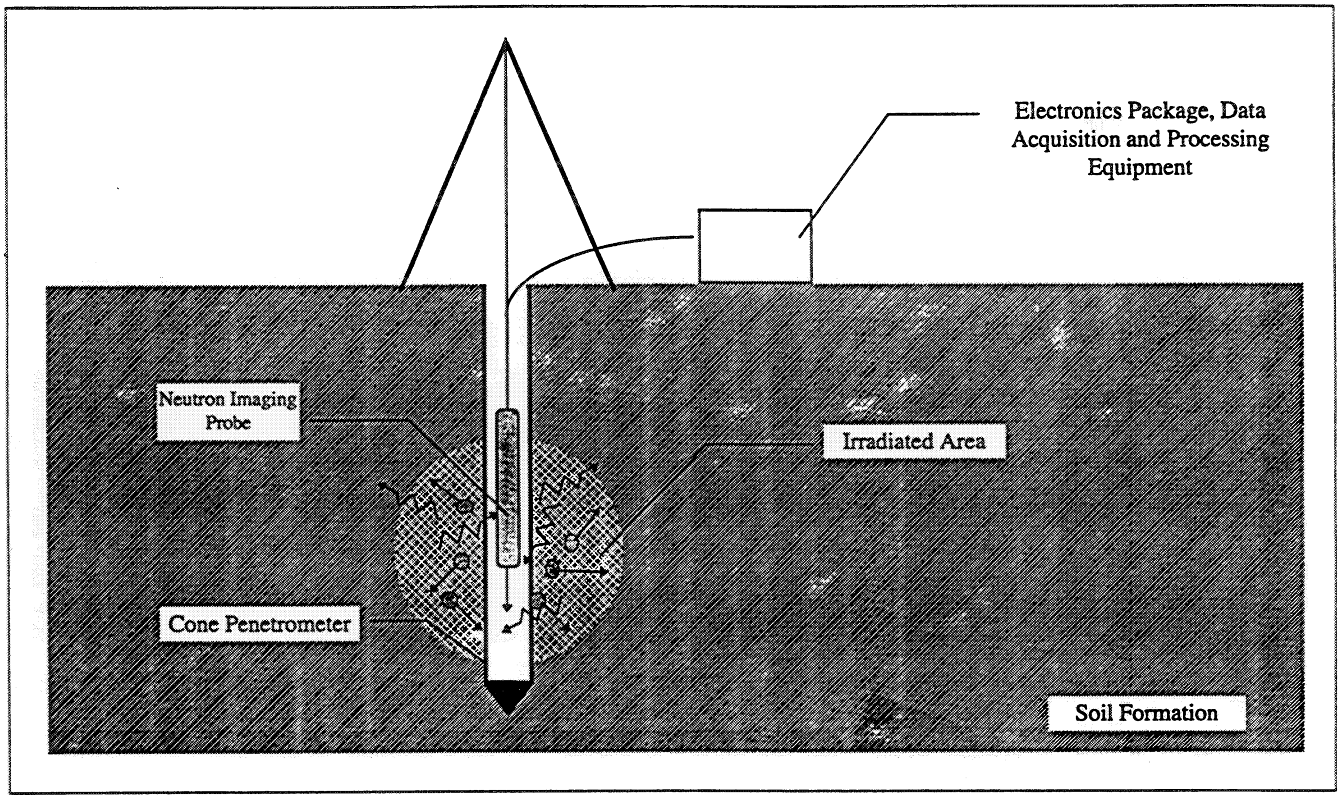


Exhibit 3.2.3.7-2: Schematic illustrating the deployment of a neutron induced gamma ray probe as devised for the survey of the MSFC CTS - deployment for wells and cone penetrometer. The probe is progressively lowered in the well or penetrometer. At repeated intervals the probe is stopped and a measurement is taken. The neutrons are sent across the casing into the formation where they interact with individual atoms. The resulting gamma rays returning towards the probe are recorded by a high resolution gamma ray detector. Information about the elemental nature of the soil is extracted from the spectra.

3.3 Technology Adaptation to Mission

As with any survey site, the CTS presents its own set of operational issues, constraints, and restrictions. We discuss these in turn below.

Permits:

The proposed survey modalities are essentially non-invasive and entail no hazardous aspects. Permits or licenses appear not to be required other than coordination of activities with the respective authorities at the ADEM, Red Stone Arsenal and the NASA / MSFC. However, for the airborne survey low altitude, helicopter based systems are preferable in addition to possibly performing such a survey over a few hours on one weekend. However, all airborne systems would comply with the FAA regulations for safety and operations which is the responsibility of survey contractors. If new equipment is added to the airborne system, the survey contractor would require recertification by the FAA. No significant modifications are contemplated to airborne equipment we plan to use for the CTS survey.

Environmental:

Portions of the CTS are heavily wooded and thick with undergrowth. In addition, streams, sinkholes, and artesian wells dot the wooded sites, not usually an environment that is easy to negotiate on foot. It may also be difficult to execute straight and level survey lines in this portion of the CTS, and thus we may use a differential GPS.

More than likely, automated survey systems can not be the choice since they are not the state-of-the-art. Manually negotiated, wheeled or simply man-portable devices are appropriate for ground-based surveys. The ground-contact modalities (*e.g.*, resistivity, seismic, GPR) should be less impacted by the rugged environment of the site, since static (vertical and lateral) corrections represent a normal part the field protocols for these modalities.

Power lines, telephone lines, water lines, and sewer lines which criss-cross the developed areas can interfere with both magnetometers and the EM devices, unless steps (signal averaging) are taken to mitigate their effects. Survey modalities involving any kind of implanted sensors are not compatible with the paved areas or the subsurface under the floor of the buildings. In such areas, the GPR and the EM techniques will be the obvious choices.

The precipitation in the site area would impact when and what survey modalities can be used. The Winter season features more precipitation than the Summer one. Normally, it is prudent to run the GPR surveys during dry periods and the resistivity (and SP) surveys when there is enough moisture in the soil, *i.e.*, in the relatively wet periods. The impact of precipitation is obviously on scheduling of survey modalities and conducting at one time those surveys that are mutually compatible. Nonetheless, some flexibility in scheduling may well be necessary.

For the Neutron Imaging survey, the surface conditions will have an influence on two different aspects of the measurements. First, the water content of the near ground surface somewhat influences the neutrons' range. The higher the water content, the smaller the neutrons' range. This affects mainly the surface measurements where the detector is moved away from the source and the range of the measurements depend on the extent of the irradiated surface. It is recommended to perform the survey during the Fall, probably in October, when precipitation is low and the ground has been dried during the Summer. The other aspect of the measurements affected by the surface conditions is the vehicle mobility. For the surface measurements, moving the water drum used for the radiation shielding will be difficult with a rudimentary set-up. Also, the electronics equipment and the generator will be located on a trailer. In the case of measurements made with a cone penetrometer, a heavy vehicle must be used and therefore the accessibility of the site is again a factor. For the CTS, the area affected by the surface condition is mainly the wooded swamp area in the Southwest part of the site; there the measurements could be made only on the road crossing this area.

Overflight:

This issue has been discussed under permit requirements. In case there is any restriction on overflight, a viable strategy would be to perform low altitude airborne surveys for an overall mapping of the site as a screening tool for the detection and delineation of AOCs which can then be the subject for detailed investigation using ground-based sensors.

Topography:

The local variations in topography will necessitate careful attention to statics corrections in processing of GPR data. Statics corrections for GPR data can be time-intensive and could increase data processing costs. Testing of surface-consistent statics routines developed for seismic data may need modifications to contain data processing costs. Even if GPR data processing costs may increase somewhat due to topographic variations, it is not any impediment to GPR surveys since the data processing costs for GPR is almost an order of magnitude lower than that for seismic.

Soil Characteristics, Vegetation and Wetlands:

The CTS soil contains some clay which may interfere with penetration by some wavelengths of RF. The extent of the interference will be assessed from resitivity and EM surveys of a limited area of the Site in mid-December 1995, and from laboratory measurements of RF properties of soil samples collected. Should the soil composition indicate some interference due to RF modalities, operational selection will be made to utilize an acceptable frequency regime and the advanced approaches and data processing techniques, we have discussed in this section.

Soil disturbing activities or vegetation removal / disturbance within the wetland or along Indian Creek raise special problems. Extensive soil disturbing activities (bulldozing, trenching, drilling) in the wetland or within 50 ft (15 m) of Indian Creek are regulated under section 404 of the Clean Water Act (CWA). Under the CWA such activities require a permit from the U.S Army CoE. Disturbances of less than 5 acres (2 ha) can be permitted under a U.S. Army CoE Nationwide 404 permit. However, no such requirement is implicit in the modalities we have selected. Early in Phase II, we will consult with the cognizant U.S. Army CoE authority, and if any 404 permit is required actions will be taken to seek such as early as possible. A 404 permit may be anticipated to require about 90 days to obtain. Because of the sensitivity of the wetland habitat and the potential presence of sensitive fish species in Indian Creek, the USFWS and Alabama State wildlife managers may come into the picture. Avoidance of vegetation removal or soil disturbing activities within the wetland or along the creek is not only compatible with the survey modalities we have selected but is also our goal. In order to minimize impacts to wetland vegetation, surface activities in the wetland should occur during the driest periods possible (August - November). Depending on the condition of the dirt access road, sampling may occur there during other periods as well. Similarly, activities along the creek should be carried out during periods of minimal soil moisture in order to minimize impacts to the soil surface and vegetation.

During the warm months and into the Autumn, vegetative overstory can began issue to some airborne RF modalities. Vegetative cover is minimal during the interval November - February. Aerial sampling during that interval will be minimally effected.

The botanical literature was searched for lists of species that might be bioindicators of specific pollutants. Only one paper was found which lists a variety of plant species that may be used to indicate the presence of specific minerals (Cannon, 1971). Cannon's paper listed only two species known from the MSFC that are known to be specific bioindicators. Black gum (*Nyassa sylvatica*) can be an indicator of Cobalt and sweetgum (*Liquidambar styraciflua*) can be an indicator of Zinc. Both species are common throughout the facility, and neither chemical is of concern in the present instance. There is no reason to believe that presence, absence or appearance of either tree will be helpful in refining the sampling scheme.

Given all of the potential climatic and environmental constraints present, the optimum period for surface-intensive sampling is late Summer- Autumn (August - November) when soils are driest and precipitation is least. The optimum period for aerial sampling is late Winter-early Spring (February - March) when vegetative cover is minimal, although soil moisture is likely to be high. Use of RF wavelengths that penetrate vegetation would make the Autumn period optimal for both aerial and surface sampling. Autumn is a period of generally mild weather, which is more amenable to aircraft operations.

The interval December - July is the period with the highest potential for surface flow that could transport pollutants. That is the interval of the highest rainfall and some of the lowest evaporation (December - May) during the year. Subsurface flows would also be anticipated to be high during that interval. Detection of pollutant plume movement would be expected to be highest during that same interval, but high soil moisture conditions would make monitoring most difficult.

Working on wet ground requires consideration of two problems in sampling. One is the ability of the sampling technology to penetrate wet ground and provide usable data. the other is the problem of getting sampling equipment into areas of wet ground without getting stuck and causing undue surface disturbance. This latter is especially critical in the wetland and along the creek. Use of technologies that are minimally influenced by soil moisture will circumvent the first problem. The second can be handled by using technologies that can be man-carried and / or can be balloon-tired-ATV-mounted. If it is necessary to work on wet ground, the ATV would seem to be the method with the least impact and the greatest likelihood of performing without getting stuck.

Trees and the underbrush present at the CTS could be of logistical concern to ground-based GPR (and shallow seismic) acquisition. The seismic modules used in processing the GPR data either require that the X-Y coordinate of each trace be known, or that the X-Y positions be regular and predictable. The processing modules need the X-Y locations to move the energy on the traces to its proper position in space and time. The distance between successive lines in a 3D survey will be less than the diameter of many of the trees in the CTS. Thus, we will need to develop a location system so that the position of each trace is ascertained and recorded. This can be accomplished with a differential GPS system. An alternative, if either is not feasible, is to skip ground locations that cannot be incorporated into a straight line survey. This option would produce lower-quality data.

Loose alluvial soil causes a greater attenuation of seismic waves than does well-compacted soil. Variations in soil properties also cause variations in travel time to deeper events. However, no modification of standard practice is envisioned due to soil types or variations in soil.

If the swampy area is dry at the surface during seismic survey acquisition, no modifications to standard practice are envisioned. If the surface is water-covered, seismic sources different from the hammer-and-plate source will have to be used.

3.4 Survey System Platform(s) Analysis

The variety of platforms, airborne, ground mobile, and satellite have been discussed under **Section 3.1.1.** Each type has its advantages and disadvantages. The airborne platforms offer very high productivity, and are generally less expensive per unit survey area. However, they can only use sensor modalities that do not require ground contact. In general airborne surveys offer lower resolutions unless sophisticated processing is available and justified such as is the case with the airborne GPR. The airborne survey platforms are normally airplanes and helicopters and they require FAA certification which the survey services companies have. Of the two types of airborne platforms, helicopter offers lower cost but has problems associated with vibrations. Thus sensors and associated equipment need to be mounted with vibration isolation which is simpler than making any analytical corrections in data processing which is neither always possible nor lower in cost. Airplane systems fly at altitudes of 1,000 to 5,000 ft which is about an order of magnitude higher than helicopter flights. However, the airplane systems cover very large areas per unit time and typically will carry multiple sensor modalities and thus per unit costs ($ / acre / modality) can be significantly lower than helicopter and ground-based surveys for similar modalities. Both airborne systems carry sufficient on-board data processing capability so decisions can be made to redo any area if indicated.

The ground-based platforms offer lower productivity and thus surveys are limited to smaller and/or suspect areas within the site. In addition, they are generally more expensive per unit area surveyed for equivalent quality in results. Thus for any complex, large environmental survey, a hybrid of the two modes of deployment is the optimal choice, each mode being used for what it does best against the framework of site characteristics and the requirements and goals of the survey.

For the CTS site and in consideration of the survey objectives relative to characterization of the subsurface underlying the MSFC, the use of hybrid (airborne and ground-based) platform modes is recommended. Platform types needed for the MSFC survey are routinely used by the geophysical survey services companies, and they can be obtained either under contract services or leased from the manufacturers and outfitted with the sensor modalities required. The latter is not recommended; the preferred choice for airborne surveys is to contract for such services particularly if they allow any reasonable equipment modification needed. They provide survey data on tapes or in any other agreed upon format to the data processing and interpretation team.

3.5 Data Processing, Packaging and Interfaces to NASA MSFC

This section describes data processing, packaging and integration approaches for only the advanced, recommended sensor modalities. For the traditional modalities, standard but at times proprietary algorithms are used by geophysicists providing contract surveys. It would be useful to integrate the algorithms for the traditional modalities with the processing modules for the advanced modalities to have a fully integrated data processing system. This may not be possible because of the proprietary elements of algorithms that various groups have developed unless some equitable arrangements can be made with these groups. This issue is worth exploring but cannot be resolved until a survey of the CTS is accomplished to determine the optimal suite(s) of modalities to be deployed for survey of much larger sites. To attempt any effort a priori at, either integration of, or entering into agreements for, different algorithms to be integrated into a package would not be very productive or cost-effective. However, the plan should be to have the survey contractors to be used for the existing modalities at the CTS provide all processed data on a MapInfo system which can be readily integrated into the NASA MSFC GIS. MapInfo system is selected because of its low cost, user friendliness, usage by several of the service contractors, and compatibility with the MSFC GIS.

3.5.1 Data Collection, Processing and Interpretation

This section provides a discussion of data processing and interpretation approaches for the more advanced modalities.

3.5.1.1 Seismic Processing of GPR Data

.A study was conducted in 1993 by HARC / GTRI to locate former trenches, buried drums, soil strata, fault traces, and water table. As a result of this experience, GTRI has developed the GPR processing flow shown in **Exhibit 3.5.1.1-1**. This flow consists of several preprocessing steps which require that data be converted and scaled to a form best-suited to the software. Corrections and several seismic processing techniques such as deconvolution, depth analysis, and migration can enhance results and ease in their interpretation. An exceptional capability for processing of GPR data using seismic analogs exists at HARC / GTRI which utilizes their own software packages and DISCO[a] processing software. Volume visualization software is installed on a Silicon Graphics Challenge platform for 3D interpretation of GPR data.

Because formats vary among operating and processing systems, several conversions are necessary to correlate the data in different systems. Data collected in the field is normally written to hard disk in some proprietary format such as that used by the selected GPR hardware systems. In order to process the data outside the manufacturer provided software package, it is necessary to convert the data to some format standard to the geophysical industry such as SEG-Y. It is also necessary to remove a DC bias commonly found in radar data. An additional conversion is needed since the software provided by GPR hardware to convert to SEG-Y outputs data in a SEG-Y format specific to IBM PCs. Data is converted to ASCII and then to the IEEE format for use on Sun workstations or others if needed.

At this juncture, it is necessary to decide appropriate units to process the data. In seismic processing packages, sampling intervals are measured in microseconds, distances in feet, and velocities in feet/second. Generally velocities range from 5000 to 1500 feet / second, and programs like Semblance (velocity analysis) work well with these units. Additional scaling may be required to tailor data to seismic programs. For instance, sampling may be in nanoseconds, distance in inches, and velocity in inches / microsecond. Typically, velocities are 20-50 percent of the speed of light, which in this case would be 2,400-6,000 inches / microsecond. Such a choice of scale may result in very few samples per trace. Typically, record lengths may be 50-200 nanoseconds resulting in the number of samples per trace being on the order of 100. Many seismic programs have built in edge smoothers or ramps that operate over 10 or 20 samples and thus could pose a problem. The data may have to be resampled at a finer interval to increase the number of samples per trace.

After adjusting the data, several corrections can compensate for factors which alter the data. Statics, elevation, and instrument drift cause jitter in the air / ground reflection. Seismic statics programs can easily correct for the jitter in air / ground reflection. These are aligned by use of cross-correlation methods. Correction for elevation changes has not been very successful since these changes may be similar in magnitude to the exploration depth. Consequently , GPR data is referenced to the surface. Leveling should not be a problem because the survey sites are located on relatively flat terrain.

Break correction is the next step in processing. Generally the start of digitization temporally precedes the instant the radar pulse went off. This process shifts GPR traces vertically in time so that time zero is the moment the source pulse went off. After statics have aligned the air-ground reflection, this process is very simple.

Once these corrections have been applied, deconvolution is the next step. Normally the radar pulse width is approximately equal to the pulse-central frequency. In order to flatten the spectrum and obtain improved

Radar Data Processing Flow

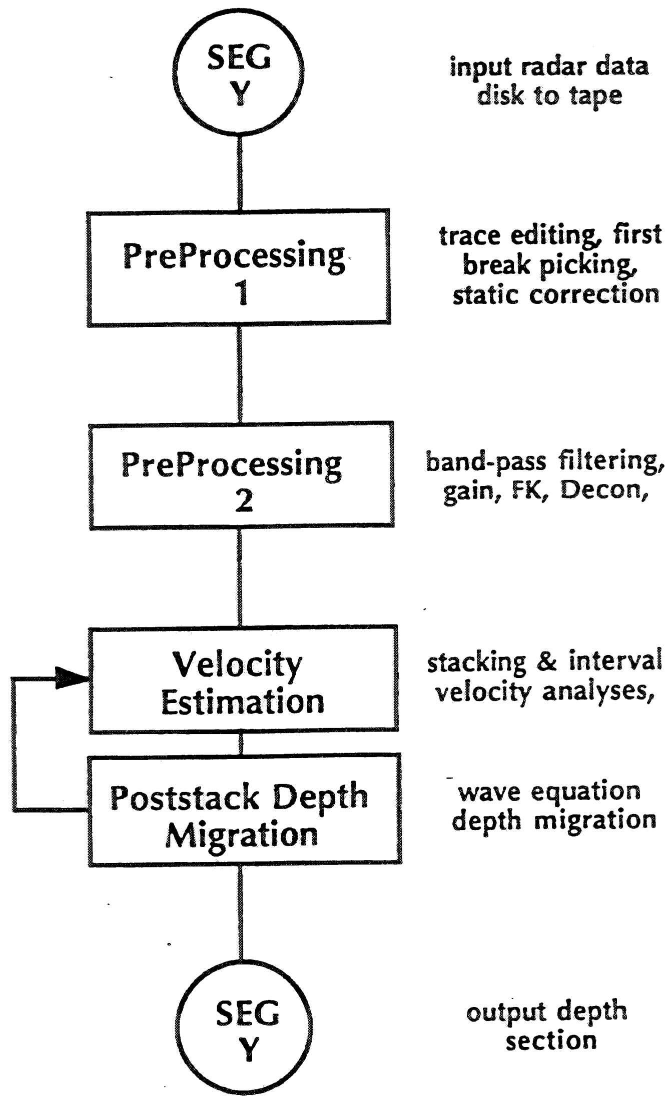


Exhibit 3.5.1.1-1: Flow chart showing the processes used in basic GPR processing. This processing flow was used to produce the image of the pipeline in Exhibit 3.2.1-7.

resolution, a zero phase deconvolution is done on a trace-by-trace basis. This process compresses the outgoing pulse, temporally reducing the length of the pulse. Deconvolution may also be used where there are short-period reverberations.

Velocity analysis is done on CMP data. Semblance is carried out to identify stacking velocities. If strong lateral velocities are present or suspected, this process is repeated at several locations on the surface. By interpolation, a velocity model is obtained for the whole line or survey. Generally, GPR velocities decrease with depth. Foreign objects in the ground could alter velocities significantly.

Migration either in 2D or 3D is the next step in the processing flow. Migration plots dipping reflectors in their true spatial positions and collapses diffracted energy. Time migration is done when the velocity model is not very complicated, that is, velocities do not vary rapidly in a lateral sense (vertical velocity variation is permitted). Depth migration is the recommended step should there be significant lateral velocity variations. Migration is the most dramatic processing step with respect to the appearance of GPR and seismic data. **In Exhibit 3.5.1.1-2**, for example, the hyperbolic event at the bottom of the GPR section will completely collapse on migration. If other events were underlying this diffraction, they would then become visible.

The final phase is visualization. This process entails loading the data on a 3D work station and adjusting the opacity so that the target event is clearly identifiable. A program available at HARC / GTRI, Voxelgeo[a] allows the user to specify data attribute ranges to be made transparent, so that the entire volume may be viewed at one time without the necessity of slicing the volume. For example, all low-amplitude events might be rendered transparent, and the resulting volume viewed in the 3D orientation will show only prominent events, **Exhibit 3.5.1.1-3**.

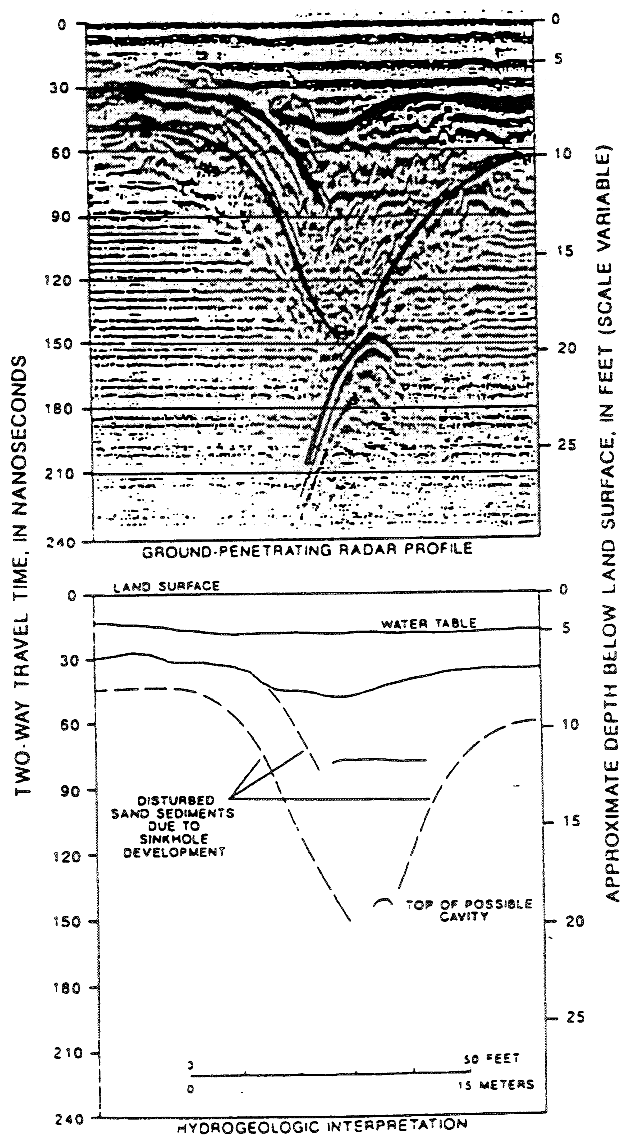


Exhibit 3.5.1.1-2: GPR profile across a sinkhole in karst topography illustrating the clear image of the feature attainable with modern GPR methods. Migration would collapse the diffracted energy at the base of the sinkhole, improving the image. From Barr, 1993.

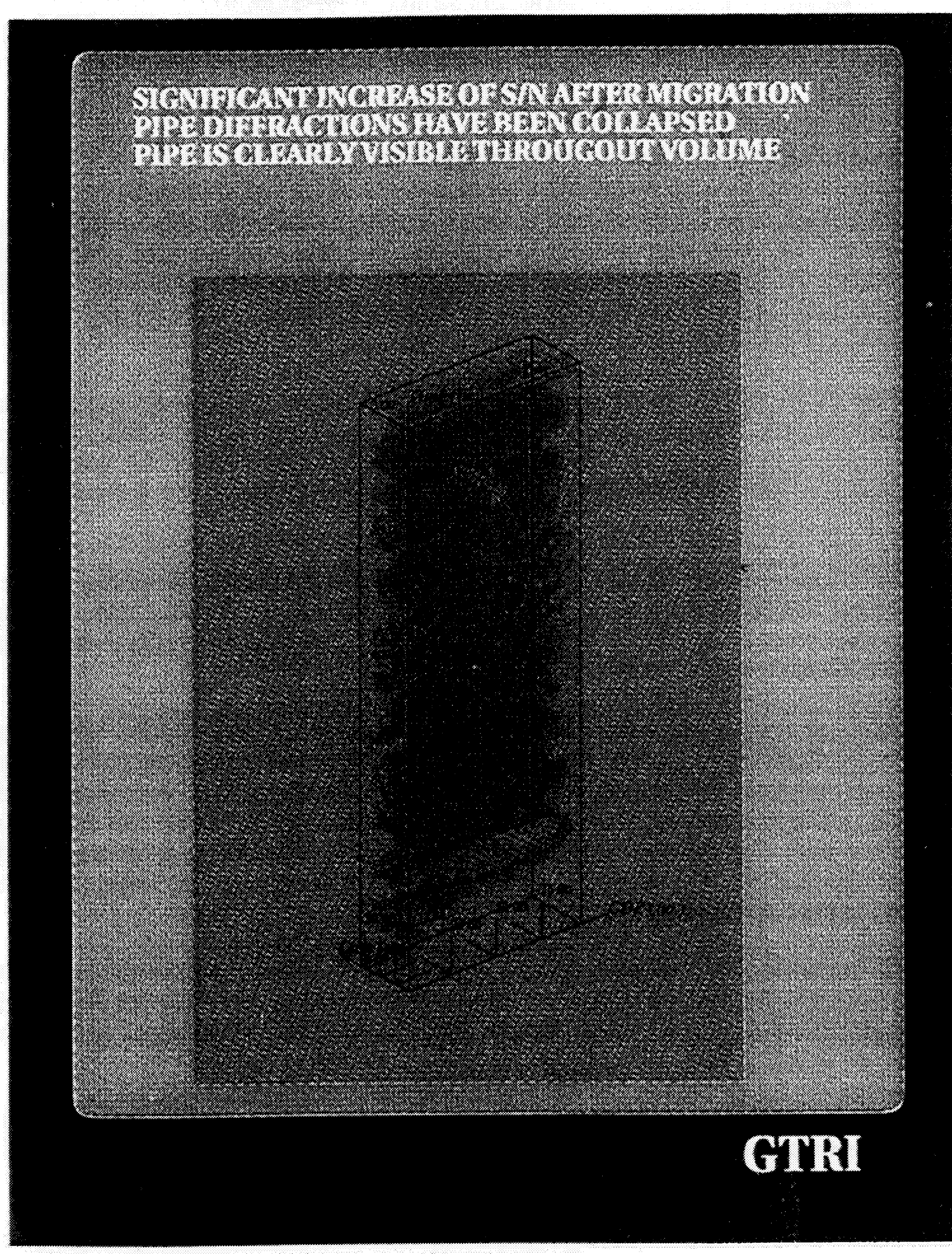


Exhibit 3.5.1.1-3: After migration and visualization using seismic algorithms available at GTRI, the underground pipe is unambiguously located.

3.5.1.2 Processing of Seismic Reflection Data

The processing flow for seismic data is essentially the same as for the GPR data. A larger number of algorithms are implemented in seismic processing than in GPR processing, but these are for the most part minor processes that increase signal-to-noise ratios. For example, some types of filtering that can significantly improve seismic data have not been found to produce improvements in GPR. There are, after all, differences in the wavefield that must in some sense limit the analog between the processing of EM waves and seismic waves, and many of the algorithms written for seismic undoubtedly stretch the analog too far to produce the desired result.

3.5.1.3 Interpretation of Processed GPR and Seismic Data

Interpretation of GPR data and shallow seismic data is accomplished by the same process, and so both will be discussed together. The first step towards interpreting the data volumes and profiles will be to tie the information obtained from the wells released by the MSFC. Variations in lithology should appear on both shallow seismic and GPR records (though the tie might be expected to be more reliable on the shallow seismic records).

The second step is to track any interpretable reflection events throughout each volume to determine stratigraphic dispositions. The locations of discontinuities may signal faults, voids, or fracture surfaces that might act as conduits for fluid flow. It is necessary to determine whether the discontinuities are due to subsurface features or are artifacts due to near-surface velocity variations (hence the need for careful application of statics corrections).

Finally, the data volumes are interpreted in terms of possible fluid conduits, including fissure zones, zones of high-density karsting, sedimentary layers with a high permeability known from the site wells, and other factors. The site of known sources of contamination will be compared with inter-site reflectivity to determine whether blanking due to dispersed contaminants is present.

The interpretation of seismic reflection data cannot be automated, and requires trained and experienced personnel. Interpretation skills cannot, unfortunately, be packaged and transferred to NASA at the completion of the project. Interpretation requires the ability to differentiate between "real" events and artifacts, a skill that comes only with time and practice. Thus, the final product delivered to NASA can only be an interpretation of the CTS survey area. The interpretation will be in two forms. The first is an interpreted digital volume in the format described below. The second is a paper map-view illustrating the surface position and depths of features mapped in the data volumes.

An industry-wide format exists for seismic data known as SEG-Y. Almost all seismic programs read and write SEG-Y files, whether or not the format is used internally in the program. With the NASA MSFC having the capability to read SEG-Y data, it would be the preferred option for data delivery of both the seismic and GPR records.

A second option would be files of the type used in Voxelgeo, the visualization program used at GTRI. Voxelgeo files are written by X-Y-Z coordinates, but are of a much lower resolution than SEG-Y files, and thus are not a recommended format for data archiving at NASA.

The most that can be said about data packaging of the seismic and GPR surveys is that, after consultation with NASA personnel, the most optimum format possible will be provided. In all probability, a programming effort will be required to transform the seismic and GPR records into a format readable by NASA software. However, it may also be the case that NASA does not want the seismic and GPR records in digital format, but only requires maps and interpretations in digital format. In either case, the programming effort should not be large.

3.5.1.4 Advances in the Processing of GPR Data

The focus of advanced techniques for processing GPR data is to allow user friendly operation and interpretation of results with minimum involvement of experts. Fundamental to processing of data obtained with the advanced GPR, we discussed in **Section 3.2.1**, is the type of incident (probing signals) used and how the returned signal is treated. Target detection, discrimination and clutter rejection are important to user friendly operation and interpretation of results without much involvement of the experts. These considerations form the basis for use of the UltraShort crafted and coded pulses in addition to achieving higher resolution and higher penetration of subsurface. These aspects are discussed in detail in Appendix III.

3.5.1.5 Neutron Imaging

For each test location, the results will consist of characteristic gamma-ray energy spectra. For well 28d and for the areas in which cone penetrometers have been used, the data will also consist of several spectra corresponding to different depths. For the surface measurements, the spectra will be collected at different locations around the neutron source. The actual chemical detection will be completely based on the energy spectra which can be specified from site specific simulations and previous experience.

Chemical characterization:
For each test location, the analysis will consist of assessing for the presence of the pre-identified chemicals by analyzing the gamma ray spectra. If the characteristic signature of a chemical is found in the spectrum, the intensity of the particular line will be recorded for that location. It is important to remember, as explained previously, that Neutron Imaging detects the presence of elements composing a chemical and not the chemical themselves. For example, DDT, TCE, and PCB's all contain chlorine. The Neutron Imaging technique will detect the presence of chlorine but would have to detect other elements composing these chemicals to trace back the exact composition of the pollutant. This will not be a problem for metals since they are already elements. For other chemicals, such as organic compounds, a true chemical characterization can be achieved only if enough of its components can be detected. However, the purpose of the Neutron Imaging technique is foremost the detection and mapping of "hot spots". Once the location of the "hot spots" has been determined, other techniques involving sampling can be applied with the knowledge of at least one of the elements of the chemical. Also, the cone penetrometers could be used to house other techniques addressing more specifically the detection of volatile organic chemicals or other chemicals of primary concern.

Modeling of potential plumes:
For the surface-type measurement, a "plume modeling" for each element detected in the test area can be accomplished by mapping the signal intensity of the element of concern over the tested area. This technique should emphasize mapping for the presence of chlorine and heavy metals. If the cone penetrometer method is used, a mapping of the underground will also be possible over the area investigated with the penetrometers.

For the Neutron Imaging technique, the final data will be a list of the identified elements of concern with their signal intensity at each test location. The available data will also include, for reference, the gamma ray spectra obtained at each location with the measurement parameters. For the areas in which a particular chemical was detected in the near surface, surface maps indicating the presence of the chemicals will be incorporated as an MapInfo GIS.

3.5.2 Data Needs and Formats

The MSFC environmental information management system and its operations are discussed in this section. This information is the basis for designing data delivery, analysis, and archiving formats for this project.

3.5.2.1 NASA Requirements

NASA MSFC requires a capability to understand and describe the subsurface geological and hydrogeological features. In addition, the information is needed to determine the pathways and fate of chemical substances released at numerous sites within the MSFC area. Knowledge and understanding of the surface and subsurface topography will be used to aid the environmental pollutant fate assessment process. The subsurface location of bedrock and the uniformity and continuity of bedrock is paramount in understanding the fate of surface contaminants.

3.5.2.2 Expected Data Products including GIS overlays

The MSFC will use numerous Digital Terrain Models (DTMs) to assess and understand the data generated during this project. Both Triangulated Irregular Network (TIN) and gridded data models will be used. 3D images will be created by using GIS data and data developed during this project. The MSFC can integrate groundwater flow and contaminants transport models into their GIS, and use GIS to develop interactive 3D volume representations of the subsurface data.

Visual inspection of the 3D images and other data can be used to determine the path taken by chemicals released at the surface. The MSFC would like to be able to "fly" through the database to investigate different release sites and potential paths through the subsurface. Future plans call for the inclusion of data from this project into subsurface models such as MODFLOW, MODPATH, and MT3D that can be used to predict the flow of subsurface water under different conditions.

3.5.2.3 Technical Requirements for Interface to NASA System

The basic unit of data for the NASA data management system is the Voxel (volume pixel). Each data point has a spatial coordinate (x,y,z, etc.). Each voxel may also have attribute data associated with it like soil type, temperature, color, line type, point, etc. **Exhibit 3.5.2.3-1** presents a sample of ASCII data used as input to MGE Voxel Analyst (MGVA). The MGVA is expected to be the main 3D volume visualization tool used by NASA for data generated by this project.

X	Y	Z	Attribute		
1454403.58	699617.29	636.00	0.00	636.00	0.00
1455990.31	695841.90	598.00	10.00	628.00	30.00
1455464.01	695452.02	599.00	10.00	629.00	30.00
1456703.70	696656.91	636.00	235.00	636.00	0.00
1454400.02	700590.77	632.80	0.00	632.80	0.00
1454400.02	700590.77	632.80	66.00	632.80	0.00
1456690.00	695836.00	627.00	428.00	627.00	0.00
1456690.00	695836.00	532.00	33.00	627.00	95.00
1456690.00	695836.00	527.00	107.00	627.00	100.00
1456690.00	695836.00	522.00	23.00	27.00	105.00

Exhibit 3.5.2.3-1: Example ASCII MGVA Input

3.5.2.4 NASA GIS System

The current system is comprised of the following Intergraph Inc. components:

(1)	IP6780334	27" 1BG color monitor
(2)	SSAM07502	Intergraph System Software
(3)	FMEM125	32MB Memory
(4)	FPLT792	CBC-S445 Full Color Printer
(5)	SJAV254AA-0000A	MGE Environmental AT 123D
(6)	SGAZ00500	MicroStation 32
(7)	SJAV244AA-0000A	MGE Environmental Manager
(8)	SJAV0559AA-0000A	Modular GIS Environment System
(9)	SJAV3400	MGE Geologic Mapper
(10)	SJAV065AA-0000A	MGE Terrain Analyst
(11)	SJAV253AA-0000A	MGE Environmental Modflow
(12)	SJAV345AA-0000A	MGE ASCII Loader
(13)	SJAV36500	MGE Voxel Analyst

Part numbers listed reference UNIX based products. Intergraph has moved all of its GIS products into the Windows NT Operating System (OS). The MSFC Environmental Office is also upgrading their hardware and software to the Windows NT OS. The following discussion of Intergraph products will be based on the

Windows NT version of the software currently sed by the MSFC. All UNIX features of the software have been maintained plus new features have been added in the NT versions.

The Intergraph Modular GIS Environment (MGE) family of mapping and GIS software products is based on the Intergraph MicroStation Computer Aided Design (CAD) software and the MGE Nucleus (MGNUC). Different applications for advanced GIS operations are layered over MicroStation and MGNUC.

MicroStation:

MicroStation is a comprehensive CAD software product with a 2D drafting engine and 3D design tools. MicroStation is completely compatible with AutoCAD .dwg files and most other CAD packages. MicroStation is controlled through a graphical command center featuring pull-down menus, tear-away tool palettes, dialog boxes, and multiple, resizable, overlapping views. All windows are simultaneously active for designing.

Powerful tools, based on Nonuniform Rational B-Splines (NURBS) technology, help crate freeform, mathematically precise surface models. MicroStation Version 5 surface modeling capabilities include full 3D Boolean operations. MicroStation has built-in, photo-realistic rendering capabilities and fly through animation. Flexible light sources, shadows, transparency, depth queuing, anti-aliasing and bump and pattern mapping create effective visualizations. Rendered views can be saved as TIFF, TARGA, Windows BMP, PICT and Intergraph RGB formats.

MGE Basic Nucleus:

MGNUC is the foundation for Intergraph's MGE family of mapping and GIS software products. MGNUC provides a single, consistent entry point for accessing MGE project data, various GIS software routines, and other application products. MGNUC offers project management, coordinate system operations, data query and access, and multiple configuration options as an efficient, affordable GIS baseline. Operating standalone or in a networked configuration, MGNUC ensures MGE integration for GIS applications and provides common tools valuable to other MGE modules.

MGNUC offers a simplified system for defining, organizing, manipulating, and presenting data throughout the various stages of the MGE project work flow. Users can define a project, create and modify data, review available geographic information, and import data from other projects. Other MGE applications modules (such as analysis, translation, and modeling) can also be accessed from this environment.

MGNUC provides a complete set of tools for coordinate system definition. It allows users to enter data into a number of different coordinate systems. MGNUC's capabilities include projection definition and setup operations.

MGNUC is an inexpensive platform for some applications, such as MGE Terrain Analyst, that require only coordinate system setup. MGNUC also prepares data for use with MGE Projection Manager to perform datum transformations and coordinate conversions.

Data Query and Access:

MGNUC gives users the ability to perform simple queries on their GIS data. Data can be reviewed using feature and Attribute specifications, or by choosing from a menu of project maps or selected attributes. Features can be displayed by selecting a map area from an overview or vicinity map. Users can also easily change the content of the graphics window or view by selecting features from a list. In addition, MGNUC provides queued-editing capabilities to locate and correct data errors. Reports can also be generated from the results of database queries. **Exhibit 3.5.2.4-1** presents the MGE Data Model.

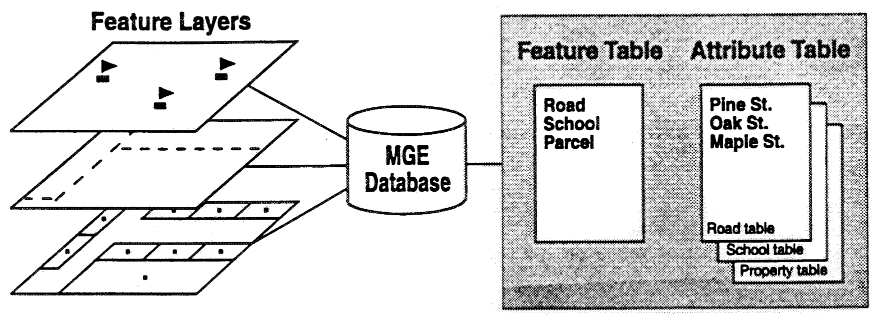


Exhibit 3.5.2.4-1: The MGE Data Model

MGE's data model is composed of graphic elements linked to descriptive attribute information in a Relational Database (RDB). Graphic elements can consist of points, lines, and area features. Point elements, such as fire hydrants, utility poles, and manhole covers, are represented as single points in the graphics file. Linear features, such as roads, rivers, and utility lines, are defined by connected points that represent linear elements. Areas are depicted as polygonal features and corresponding area centroid. The area centroid are points placed within the area feature on which the area's attribution is attached.

All these graphic elements are linked to Relational Database (RDB) information that further describes and defines each individual feature. For example, a linear graphic element may be defined as State Highway 29. This geographic feature can be further attributed as an asphalt, four-lane, limited-access highway that was last resurfaced in 1984. The MGE data model allows a virtually limitless amount of descriptive information to be attached to a graphic element.

In addition, Relational Interface System (RIS) facilitates communication to the RDB management system over the network. The use of RIS enables multiple workstations to communicate with the database server simultaneously. This cuts costs by reducing the number of database licenses required.

MapInfo Data Translation:

MGNUC provides streamlined routines for integrating with MapInfo resources. Existing MapInfo data can be quickly incorporated into MGE projects as MGE features. These conversion routines open a window to a wealth of existing geographic data which can be purchased from MapInfo to quick-start or augment any MGE project. Likewise, MGE Data is easily converted into the MapInfo data format for intensive tabular data analysis or distribution to other users. **Exhibit 3.5.2.4 -2** presents different configuration diagrams for MGE applications layered over MicroStation.

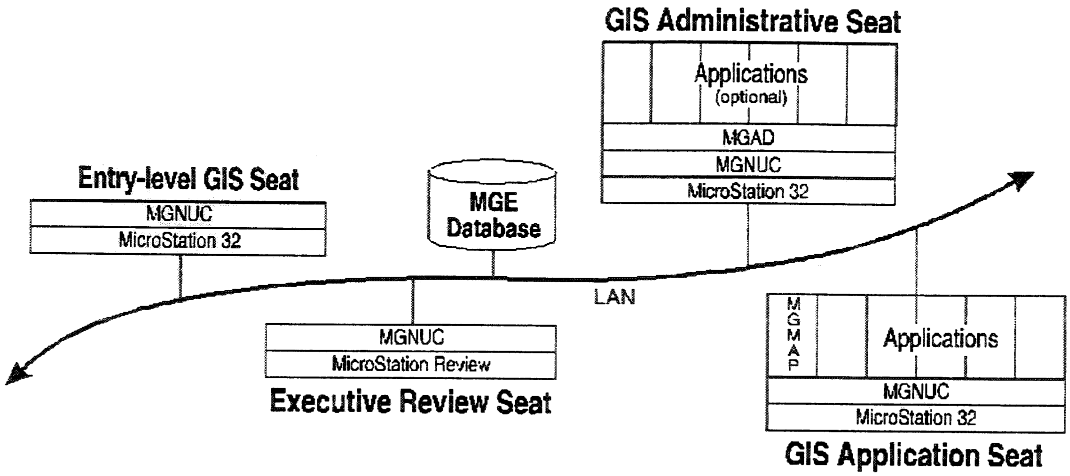


Exhibit 3.5.2.4-2: Configuration Diagrams

Multiple Configuration Options:

When configured with MicroStation 32, MGNUC provides project management, coordinate system capabilities, accurate geo-referencing of spatial data, and data collection and manipulation tools. This basic, entry-level configuration also serves as a platform for all MGE applications that do not require a RDB. For applications requiring a RDB, MGNUC requires MicroStation 32 on the node, MGE Basic Administrator (MGAD) on the Local Area Network (LAN), and an Intergraph RIS server to provide a link to the RDB. This allows the RDB data to be incorporated into the MGE project. MGNUC's feature / data access tools allow users to query and review their data.

Some users may not need the ability to change project data, but may still want to view the information. For users wanting read-only access to the MGE project database, MGNUC can be configured with MicroStation Review on the node, a RDB, MGAD, and a RIS server on the LAN. This configuration provides an extremely affordable "executive review" seat, easily added to any MGE network.

MGAD:

MGAD provides project and database management tools that link the Intergraph MGE to a RDB. For MGE applications that use an RDB, MGAD provides project definition and maintenance tools for defining database schemes, map categories, features, and attribute tables. MGAD is required on at least one seat on the LAN when a RDB is configured as part of an MGE system.

Establishing the Database Relationship:

MGAD uses Intergraph's RIS to communicate with a variety of RDB management systems either locally or across a network. RIS makes the RDB transparent to the user, enabling the software interface and menus in MGAD to be consistent regardless of the specific database being used.

Project Setup and Definition:

MGAD offers a user-friendly interface for MGE project setup and definition. Users are guided by a forms-driven interface to define project schemes, map categories, features, and attribute tables. In addition, users can take advantage of the flexible data structures and power of RDB technology through the creation of attribute table domains, joins, and views.

Tools for the Future:

MGAD provides essential setup and management functions that prepare data for processing with MGE Base Mapper and other MGE application modules. MGAD tools provide an administrator with the ability to implement and maintain an MGE project data model and / or database relationships. MGAD also provides several parameter-definition tools that are prerequisites to other MGE application modules.

MGE Base Mapper:

MGE Base Mapper (MGMAP) provides tools for capturing and managing GIS project data in MGE. MGMAP includes both interactive and batch tools for data entry, cleaning, and manipulation. MGMAP data capture tools include interactive digitizing options. Users can digitize features and load any associated attributes in the same session.

MGMAP allows users to locate and edit attribute information through interactive query on graphic elements representing features. Attribute queries can be made directly to the MGE project database or obtained through selection of the desired graphical object representing a feature. Attribute information can be added or modified through a variety of interactive and batch tools. Bulk database loading tools are provided for efficient capture and storage of existing graphic data attributes in the RDB.

MGMAP offers easy-to-use utilities for feature creation and symbol modification. Feature creation can be done while digitizing or at a later time. Both interactive and bulk routines are provided for turning graphic elements into features linked with the RDB. Resymbolization functions allow users to alter graphic resymbolization at any time, either interactively or through batch processes.

MGE ASCII Loader (MGAL):

MGAL is an MGE module for loading and unloading ASCII data into MGE project format. MGAL accepts ASCII files containing coordinates for vector geometry and associated attribute information. Geographic features are generated and new attributes can be inserted into MGE project databases. With MGAL, it is possible for users to incorporate data collected in other GIS environments when they integrate MGE into their systems. Because some systems output information to several ASCII files, some reformatting may be required to prepare a single ASCII file for input to MGAL. Users need only to write simple scripts to format the ASCII data so that it is readable by MGAL. MGAL will also unload feature-tagged vector geometry with or without associated attribute data from a MGE project into an ASCII file.

MGAL processes holes and islands within an ASCII file. A hole is a void within an area boundary where its boundary has the same feature tag as the exterior area boundary that contains it and does not contain an area centroid. An island is an area boundary feature contained within another area boundary feature which has its own area centroid and may be a different feature than its exterior area boundary.

MGAL's easy-to-use forms interface facilitates the ASCII format definition, modification, and the actual loading and unloading. To further assist with format definition, a file reviewing capability is also available. MGAL's command-line interface can be used to speed batch processing.

Applications for MGAL include loading survey data, GPS, or maritime point data, as well as digital terrain data files and data from the government or other GIS vendors.

MGE Terrain Analyst (MGTA):

MGTA is a component of the MGE family of application software tools for integrating, analyzing, and presenting geographic information. MGTA provides the tools for cartographers, scientists, and GIS planners to manage 3D surface features.

MGTA utilizes both the TIN and grid data formats to produce vector and raster output. Map projections and coordinate systems are built into every surface model. The ability to integrate different types of source data gives users optimal flexibility in project design and implementation.

MGTA is based on the MicroStation graphics platform and the Windows NT Workstation 3.5 OS. Configure MGTA with MGNUC for mapping and DTM projects, or incorporate a RDB for a complete 3D GIS analysis solution. MGTA has an intuitive, easy-to-use, graphical interface as well as a complementary set of command-line functions for creating and manipulating DTM data on disk. All of the features of MGE Modeler (MGM) for Windows NT are within MGTA. MGTA is used to configure data files for the development of DTMs and for use by MGVA. **Exhibit 3.5.2.4-3** presents a sample of one of the input files for MGTA that is used with the cross reference file shown in **Exhibit 3.5.2.4-4..** Together these files can be used to create DTMs.

```
* Model: (Model Name)
* Units: Meters
POINT_FORMAT POINT_NAME NORTH EAST ELEVATION FEATURE
* Regular Points
points {1  234113.5802 1522199.8002 182.880 regular
32  233804.9702 1521229.3402 182.880 regular
101 232734.6602 1519738.5002 182.880 regular
112 232989.5402 1519156.1902 182.880 regular}
* Spot Heights
points {118 232674.9402 1518884.8602 182.880 spot
120 232563.9002 1518829.8302 182.880 spot
* creates a breakline feature and outputs
* to the break.xyz output file
LINE ( 301 347 353 ) breakline
* ridge
points {360 229345.6502 1520232.8602 198.120 scratch
401 230718.8902 1518898.1302 198.120 scratch
403 230722.8102 1518796.9702 198.120 scratch }
* creates a ridge feature and outputs
* to the ridge.xyz output file
LINE ( 360 401 403 ) ridge
* points for model edge
```

Exhibit 3.5.2.4-3: Sample Input File for MGTE

```
* xyz.xrf - sample cross-reference file for adftoxyz
* the second field (if listed) must be a keyword.
* If the second and/or third fields are omitted,
* the last KEYWORD and/or filename will be used.
*
*
* feature
xyz-type
xyz-filename
* figure name
*------------------------------------------
regular      REGULAR_POINT    regular1.xyz
breakline    BREAK_LINE       break1.xyz
spot         SPOT_HEIGHT      spot1.xyz
obscure      OBSCURE_AREA     obscure1.xyz
edge         EDGE             edge1.xyz
fault        FAULT            faults1.xyz
contour      CONTOUR          contours1.xyz
check            CHECK_POINT      check1.xyz
plane        PLANE            plane1.xyz
ridge        RIDGE                ridge1.xyz
drain        DRAIN            drain1.xyz
pit          Pit              pits1.xyz
peak         PEAK             peaks1.xyz
```

Exhibit 3.5.2.4-4: Sample Cross Reference Used in MGTA

MGVA:

MGVA is a general-purpose data visualization and analysis tool that helps scientists and engineers understand the relationship between different attributes within 3D volume data sets. Characteristics within the volume may be described numerically and are not necessarily homogeneous. These can be physical characteristics (such as density, porosity, temperature), chemical characteristics (such as chemical concentrations), or abstract characteristics (such as standard error or probability).

Model Structure:

Model structure must be 3D data grids generated either by the routines that MGVA provides or by external modeling packages. Several different grid structures are allowed:

* Uniform grids, in which the grid spacing along the three axes is constant and identical along orthogonal axes (cubic voxels)
* Regular grids, in which the grid spacing is different but constant along each orthogonal axis
* Rectilinear grids, in which the spacing varies along each orthogonal axis
* Structured grids, in which each edge of each voxel can have a different length (hexahedron), allowing the use of data which, for example, has been modeled to conform to physical geological formation and shapes

Model Input and Output:

MGVA accepts input from any grid-based modeling package (other than finite element models). A standard ASCII-data format is provided that allows multiple characteristics or attributes to be loaded into the same model. For example, porosity, permeability and uncertainty values can be included together. Reformatting of the source data into the standard format must be performed prior to loading. In addition, data grids generated from contour maps of attributes at different elevations can be loaded directly from ASCII grid files or from the following Windows NT products: MGTA, MGM, and MGE Grid Analyst (MGGA). All data sets can carry a georeference for automatic co-registration with area maps and drawings within MGE.

Modeling:

MGVA provides five simple analytic-interpolation routines that allow a model to be generated from sparsely sampled data. Interpolation can be done globally using all sparse points within the data set or it can be done locally using points within a user-specified restricted area of the data set.

Visualization:

Several visualization displays are provided including chair diagrams, cross sections (at any user-defined orientation), iso-surfaces, and iso-solids. All displays allow you to define a percentage of transparency permitting visualization of multiple objects inside one another. They can be trimmed to any extent to improve comprehension and visualization, and then placed on different levels to allow independent or combined data displays. Three display modes are provided: sketch, wireframe, and shaded. Wireframe mode is useful for rapid determination of display characteristics, such as an iso-surface attribute value-of-interest, before fully rendering a graphic display. All types of PCs capable of running Windows NT can run MGVA with acceptable display performance using an appropriate display mode.

Analysis:

Any iso-surface or portion of an iso-surface can be selected for surface area and volume calculation. The volume between iso-surfaces can also be calculated, and the values of the attributes integrated (summed) across the volumes. Using Irregular volumes, you can graphically query relationships between volumes. For example, when two contaminant plumes intersect, they can become highly toxic. You can display the intersection and calculate the volume of the intersection above or below the water table. Crossplots are used to analyze attributes by plotting any attribute against any other attribute and color coding the results by a third attribute. This function is also a Quality Assurance / Quality Control (QA / QC) tool that allows you to graphically locate any anomalous data that may need to be removed before interpolation. Simple statistics and histograms of the model or of the sparse points can be calculated allowing you to become familiar with the data before, after, or during visualization, analysis, and manipulation.

Manipulation:

Manipulation of numerical models can be done graphically with MGVA. Based on knowledge and experience, a scientist can interpret and edit volume data by graphically manipulating the numerical model within MGVA. These new models can be saved or output as ASCII files to import to other external programs.

Features and Benefits:

<u>Versatile Data Input</u>

- *(a)* Enables loading of sparse 2D and 3D modeled ASCII data
- *(b)* Provides multiple algorithms for modeling

Interactive creation of graphic displays

(a) Improves visualization of 3D spatial data using iso-solids and cross-sections;

(b) Enhances understanding of multi-dimensional data relationships;

(c) Allows concurrent display of multiple models and attributes;

(d) Provides interactivity for any PC by using multiple displays modes

Automated Analysis

(a) Provides rapid surface-area, volumetric and aggregate calculations

(b) Enables graphic boolean operations for 3D volume queries

(c) Allows attribute crossplots to reference location data, improving the understanding of anomolous data

Sophisticated Volume Manipulation

(a) Enables interactive editing or localized reinterpolation of 3D modeled data

Integration with the CAD, GIS and Office Applications

(a) Allows true geographic coordinate readout

(b) Provides easy co-registration of 3D data with maps

(c) Accepts Intergraph grid files (.grd files)

(d) Allows ASCII data to be imported from third-party modeling packages

(e) Provides CAD file input / output using MicroStation or AutoCad

(f) Integrates smoothly with other office products using simple cut and paste capability

Stand-alone Application

(a) Requires no pre-requisite software

Applications

(a) Volume modeling with heterogeneous characteristics

(b) Hazardous Site Characterization

(c) Toxic Plume Modeling

(d) Mine Orebody Modeling

(e) Natural Resource Modeling

(f) Reservoir Engineering

Software Requirements

(a) Windows NT 3.51

Hardware Requirements

Minimum

(a) 486 16 MB memory

(b) 256 Color

(c) 1024 x 768 pixel resolution

(d) GLZ graphics

Recommended

(a) TD-4, 64 MB memory

3.5.3 Final Data Products

The anticipated final data products shall include maps, data tapes with MapInfo GIS for interface with NASA GIS, and reports unless required otherwise.

3.6 Systems Analysis, Design, and Integration

A geophysical environmental survey of the subsurface underlying the MSFC that meets certain requirements is the principal interest of the MSFC NASA neither needs nor is probably concerned with acquiring any systems for geophysical surveys. In this context, the term "system" represents an integrated survey configuration employing one or more sensor modalites that together satisfy all key requirements of the MSFC at an acceptable cost. The concept of integrated survey as a system is discussed here.

3.6.1 System Requirements

The key system requirements derive from the goals and measures of success postulated by the MSFC for the geological, hydrogeological and contaminant characterization of the subsurface underlying the NASA MSFC. These goals and measures are recapitulated in **Section 3.1.** In brief, they can be stated," define and delineate to sufficient depth and resolution all subsurface features that influence the fate and transport of chemicals of concern in the underneath." This information is essential to design and implement viable and cost-effective remediation approaches. Additional requirements derive from site characteristics including its size, scope of activities on the site, and the schedule of the survey required.

3.6.2 Geophysical Survey Systems and Concepts

Geophysical surveys are conducted using both airborne and terrestrial platforms. Each of these modes use one or more sensors for exploring the subsurface. Sensor information is integrated with a data acquisition / processing system, a geographic information system, and a position reference system. The airborne surveys are used for large surveys and for gaining an overview of the survey site; the feature resolution depends on several factors associated with a system and its operations, including the type of the sensor(s) used. The ground-based surveys are normally used for more localized views, and they yield, in general, resolutions that for the same sensors are higher than those with the airborne sensors.

The cost of leasing (owning) and piloting an instrumented aircraft or helicopter is high. Thus, survey companies prefer to use an airborne system with an integrated set of several geophysical instruments, and common electronic, data-acquisition, and navigational packages; different types of surveys can be accomplished at the same time with very high productivity. The result is a relatively low cost per unit area of survey. In important contrast to the aerial surveys, ground-based surveys are typically conducted on a modality-by-modality basis by geophysicists specializing in their own particular sensors. That is, the seismic specialist will arrive at the survey site with his sledge hammer, geophones, power supplies, and data recorders. The seismic specialist will image his data sets with his own stacking, move-out, migration, and display algorithms. The EM specialists will travel to the survey site with their instruments and conduct an EM survey. They will process their data sets with their inversion algorithms and use their display software to interpret the recorded data. Traditionally, these professionals will pass their findings on to the organization that contracted for their surveys, where an in-house specialist will fuse the data sets on entry into a master GIS. Relative to the aerial surveys, the productivity of ground-based surveys is lower and thus in general they are more expensive per unit area covered. Obviously, the optimum approach (*i.e.*, an optimum survey system) is some combination of the airborne and ground-based geophysical survey modalities. The optimum survey system is determined by tradeoffs between the mix of modalities to be used and cost for the given set of survey requirements.

Cost Estimates:

Various geophysical survey modalities relevant to the MSFC requirements were reviewed in **Section 3.1.** This review included in each case an estimate of the cost per acre of the survey. The quoted figures include some geophysical interpretation and computer inversion, but not data fusion or computer visualization. For the existing methods, the cost data were obtained through conversations with different geophysical survey service contractors. There was a general reluctance on the part of the service contractors contacted to provide written estimates without knowing full specifications of the site and survey requirements. However, they did provide what may be considered preliminary estimates which we consider in most cases to be somewhat lower than what it might cost when invited to conduct the survey. The reason for our caution is that most of the survey services contractors, being small businesses specializing in one or two modalities, will not risk the loss of a bid opportunity for a survey centered around their specialty.

For surveys using advanced sensor modalities, we estimated costs using standard cost analysis practice. Advanced techniques such as Neutron Imaging will require some adaptation effort before using them for geophysical work on-site in the field, the cost of adaptation was amortized over 50,000 acres of survey over a five year period. Based on the stated amortization scenario, this adaptation component adds on the average about $20 per acre. Appendix III presents the cost of field adaptation of Neutron Imaging for geophysical characterization.

Typically, geophysical surveys entail two categories of cost elements: Fixed Costs (capital equipment, support facilities and personnel, etc.), and Variable Costs. Fixed costs must be paid whether the geophysical equipment is in the field or not. Capital costs are generally associated with the cost of equipment that can typically be written-off (depreciated) over a period of more than one year. Purchases of airplanes, sensor systems, computers, etc., are good examples of such costs. Fixed support costs include, for example: annual insurance premiums, salaried employees, building leases, and maintenance contracts on equipment including office equipment, asset based taxes, license fees, etc. The variable costs are expenses that relate directly to the conduct of a particular survey. Examples of such costs are deployment and support of equipment and personnel to the specific survey site, equipment rentals, temporary help, site specific survey permits, data processing, and reproduction / publications, etc..

The cost of a survey per unit area is very sensitive to the cost of deployment to the site and staging for conduct of the survey. These costs per acre increase rapidly, going disproportionately higher as the survey size gets smaller. There is also a certain minimum cost for each modality where any measure like "cost / acre" loses meaning.

Geophysical surveys vary widely in price. Petroleum and mineral explorations involve the large-scale exploitation of natural resources and thus entail elaborate surveys with high price tags. Geotechnical surveys, by contrast, are often mandated by local building codes--and so are often considered a no-value-added expense and thus conducted on a shoe-string budget. Environmental surveys usually fall between these two extremes, except at hazardous, toxic, or radioactive sites, where their prices may surpass $1,000 per square meter.

The MSFC occupies slightly over 1,800 acres which is too large an area from the standpoint of just the ground-based surveys alone, particularly if the subsurface feature resolution requirement is high. For high resolution and to depths of about 20m, the cost can be in the range of $3,000 to $10,000 per acre ($6 M to $18 M), depending on several factors that include the relative number of 2D and 3D maps produced, the extent of the areas required to be surveyed with the highest resolution and other performance requirements, and weather conditions, etc.

Airborne surveys are generally cost-efficient when applied to larger test sites (> 50 acres). However, they have been cost-effectively used in several cases on as small a site as 25 acres with helicopter-borne sensors (AES, Inc). Helicopter-based surveys are therefore not only candidates for both the survey of the CTS and the overall site underlying the MSFC jurisdiction, but their use in combination with the ground-based surveys can lower survey costs.

Consider a survey scenario for the MSFC site taken as 1,800 acres. This scenario involves first an airborne survey of the entire site that includes the sensor modalities of FDEM, Magnetometry, Video Imaging and GPR. The system is equipped with a GPS.

The aerial surveys are used to produce 2D maps of the entire 1,800 acres with the objectives of providing quality characterization in terms of 2D maps revealing AOCs. These AOCs are then candidates for ground-based surveys with high resolution and chemical characterization. Clearly, it is unlikely that the AOCs at the MSFC will cover the entire site. Based on the maps of the site provided by the MSFC, the SWMUs / AOCs appear to be around 10 percent of the site. However, we will assume that they cover 30 percent of the site or about 540 acres. Moreover, we assume that the ground-based surveys are conducted independently of one another by independent geophysical contractors, but that they use a common set of survey lines (for data registration and computer visualization). We also assume that each geophysical contractor will interpret, invert, and forward their data independently of the other contractors as digitized tapes or diskettes in a MapInfo format. The data fusion and computer visualization will be performed by the Prime Contractor.

Exhibit 3.6.2-1 on the following page provides a summary of survey costs for the 1,800 acre site under the stated scenario.

Survey Modality	Cost		
	Minimum	Cost / Acre	Total
2D Aerial Survey (1,800 acres):			
GPR / Video	30K	1,000	1,800K
EM / Magnetometry	20K	100	180K
Satellite Imagery	5K	5	9K
(2D + 3D) Ground Survey (540 acres):			
Magnetometry	10K	200	108K
FDEM (Two Modes)	15K	500	270K
TDEM (Slingram)	15K	500	270K
Monostatic GPR	10K	1,000	540K
Resistivity	10K	5,000	2,700K
Magnetotellurics	10K	1,000	540K
Multistatic GPR	25K	3,000	1,620K
Multifold Seismic	25K	3,000	1,620K
Neutron Imaging	25K	500	270K
Total (Airborne + Ground-based) Integrated Survey Cost 9,927K			

Exhibit 3.6.2-1: Integrated Survey Costs for 1,800 Acre Site

If the entire 1,800 acre area were to be surveyed only by the ground-based modalities shown above for 30 percent of the area, the total cost would be about $24M ((9,927K-1,800K-180K-9K-540K) x10/3). By the same token, if the air modalities were applied to obtain 3D imaging of the entire 1,800 acres which may not be possible by all airborne modalities (*e.g.*, Neutron Imaging) and to the extent of penetration and resolution achieved with the ground-based modalities, the increased cost would be largely in data processing. If the increase in cost for this scenario were by a factor of 3 the total cost for the 1,800 acre is projected at $6M. To this, one must add about $1M 1,800 acres x $500 / acre) for the cost of ground-based Neutron Imaging of the site. Moreover, the information quality and the depth of penetration by total 3D survey can be expected to be somewhat lower than the integrated hybrid approach, at least in the critical sections of AOCs. Thus, the data may still need to be supplemented with information from limited (about 5 to 10 percent of the area) areas subjected to detailed investigation by ground-based surveys. Considering all these factors, the cost of essentially fully airborne survey of the entire MSFC site is projected at about $9M.

The above is an example scenario. In a real situation, it can be expected that detailed ground-based surveys by multiple sensor modalities would not be necessary for more than 10 percent of the total site area, and that too may be liberal. Even at 10 percent , the survey cost, using the integrated hybrid survey scenario, is estimated at about $5M. Of course, one needs to add to this amount the cost associated with data fusion from sensors and for computer visualization. It is difficult to estimate those costs at this time beyond a guess. About $1M appears to be reasonable.

In addition, it may be advisable to add certain costs for use of the advanced modalities to obtain confirmatory information for chemical contaminants (*e.g.*, Neutron Imaging) and for GPR technologies for possible significant increase in penetration and data analysis methodology allowing target detection, discrimination, and geological interpretation without much involvement of the geophysical experts. These elements may likely add $3M to the total survey of the site underlying the MSFC but could provide NASA an added field of excellence in exploring what lies in the "space" underneath the surface of the earth better than anything else. A dictum of the decades to come may well be that "what we do not know about what lies buried underneath can deeply hurt."

3.6.3 Selected Survey Concept

The requirements of the MSFC for geological, hydrogeological and contaminant characterization of the subsurface underlying the MSFC are diversified, complex and fraught with challenges from site conditions including buildings, active routine use, wetlands, and others. Thus no single non-invasive sensor can by itself provide the total information required. Multiple non-invasive sensor systems incorporated on both the airborne and terrestrial platforms will be necessary. **Exhibit 3.6.3-1** shows the concept of an overall integrated survey system. The selected sensors have been identified in **Section 3.1.4.** The integrated survey systems and approach have been discussed in **Section 3.6.2** above. We have also introduced certain advanced concepts for subsurface investigation. It is important to field those, at least for the CTS survey, before any decision can be made relative to their use gainfully in the large scale surveys where such concepts could entail considerable benefits that include lower cost, higher resolution sufficient to resolve small UXOs and the like artifacts, detection and discrimination of targets without the extensive needs for expertise of a geophysicist, and others.

3.6.3.1 System(s) for CTS Testing

The integrated survey, depicted in **Exhibit 3.6.3-1**, involves both airborne and ground-based surveys with different sensor modalities. Airborne survey would be used to delineate AOCs at the CTS site with the highest possible resolution. The ground-based modalities would be used to survey AOCs in detail as well as for surveying the subsurface underneath the buildings at the site. Two modalities (Resistivity, Monostatic GPR), in particular, will be used for survey of the subsurface under the buildings; the resistivity measurements will be around the perimeter of the building on the outside and the GPR measurements, that require implanting of no electrodes, on the floor inside. In addition, highly limited areas of the CTS will be investigated with Neutron Imaging and the advanced GPR which would involve a simple modification of the existing GPR at HARC or the one from System and Software, Inc.

3.6.3.2 System(s) for Full-Scale Usage

The survey system and concept for full-scale larger geophysical surveys of the subsurface is essentially an integrated survey comprising both the multiple airborne and ground-based sensor modalities; the mix of these would depend not only on the site characteristics but also on the nature, extent and quality of the information required. The goal of choosing the mix will be to provide the key data required while limiting the use of

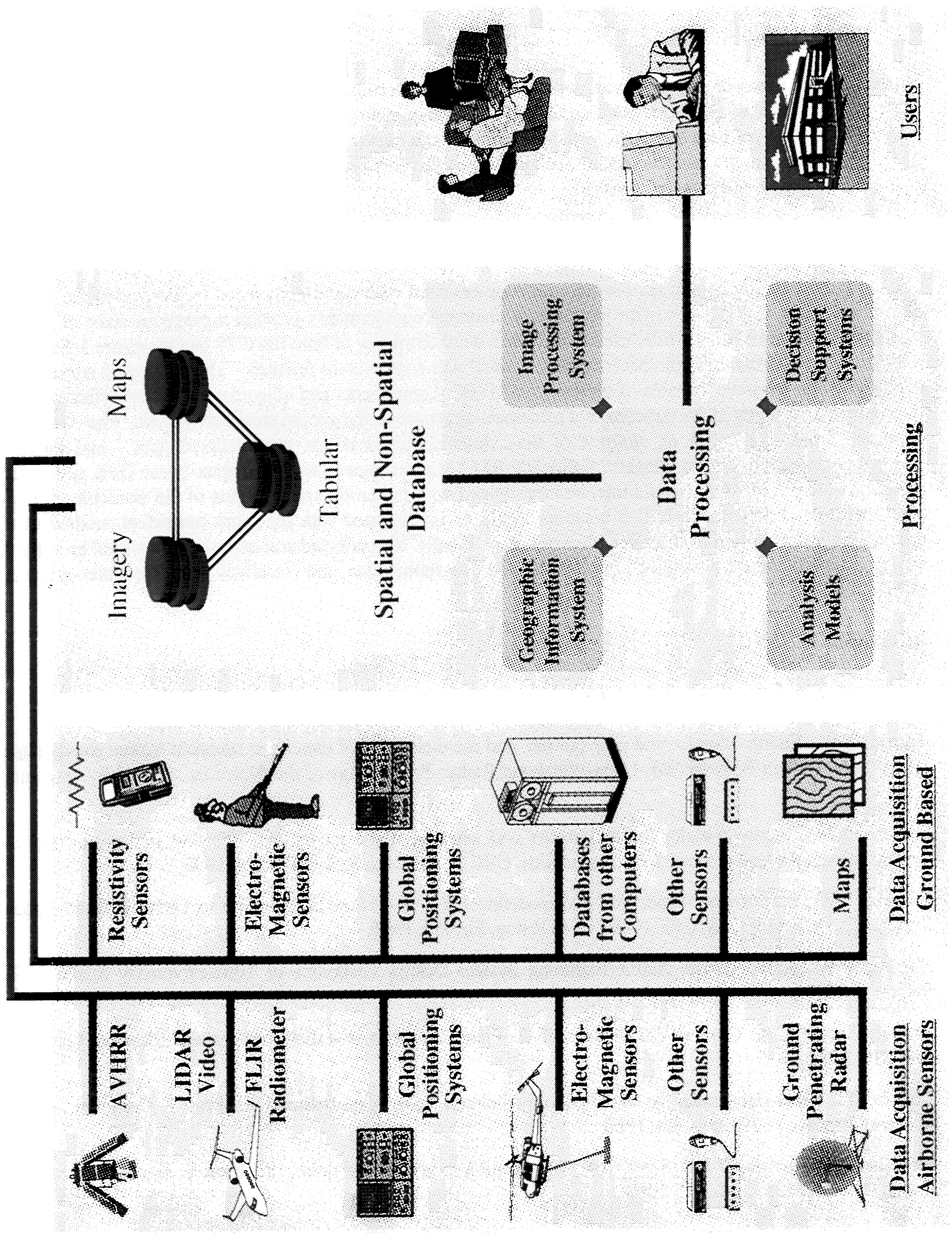


Exhibit 3.6.3-1: Concept of an overall Integrated Survey System

relatively more expensive ground-based modalities to selected sections of the site. Under such a scenario, large scale geophysical surveys for subsurface feature and contaminant mapping can be contained in the range of \$1,000 to \$5,000 per acre of the site with reasonable characteristics. For more complex sites where ground-based modalities are the only choice and the majority of the area is to be surveyed providing quality data, the cost per acre can be in excess of \$12,000.

3.7 Conclusions

The currently existing geophysical techniques supplemented with certain advanced techniques in the area of data processing, GPRs and in-situ mapping of chemical contaminants provide a powerful suite of survey modalities that can be successfully used to provide a detailed survey of both the CTS and the entire MSFC site relative to the subsurface geological, hydrogeological and contaminant features. The postulated surveys are essentially non-invasive, capable of meeting the MSFC requirements and objectives, and cost-effective. We recommend an integrated- as opposed to a piecemeal-approach to the geophysical survey task. The integrated approach would start with an analysis of the available historical and observational data - and then be supplemented with overhead imagery, Helicopter EM / Magnetometry, and Helicopter-borne GPR and Video Imaging. Identified AOCs would then be investigated with the productive versions of the available ground-based sensors. Likewise, identified hotspots would be investigated with the more competent modalities to provide higher resolution of the subsurface features. Finally, the collected and inverted data would be entered into a master GIS, where it would be fused with other geographic data, and visualized using computer-graphics techniques.

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Section 4
Survey Design and Plan

4.0 Survey Design and Plan

The CTS at the MSFC, Huntsville, Alabama has a total area of about 85 acres to be surveyed. In **Section 3.0**, an integrated survey was selected as the appropriate strategy. This survey involves first an aerial survey of the site to obtain an overall view of the site and to identify AOCs for more detailed surveys. Although, some detailed surveys of AOCs could be performed by aerial methods, diverse ground-based surveys will need to be performed. Clearly, multiple sensor types will be used in both the aerial and ground-based surveys in order to generate the diversity of information required, both to characterize the CTS and to demonstrate that the selected survey modalities satisfy the measures of success established by the NASA MSFC. In fact, the CTS survey should include a greater number of sensor modalities than what may be finally warranted for survey of the entire MSFC site. The results available from the CTS survey could be expected to influence the final choice of sensors because geophysical sensor performance not only depends on site conditions but they provide different information, often complementary.

4.1 Survey Lines And Structure

Various factors that influence both the design and lines (and grid) of a specific survey include: *(a)* the type and quality of information required, *(b)* site factors (soil, topography, structures, vegetation, etc.), *(c)* usage activities at and in proximity to the site, *(d)* any specific site area where definitive characterization exists that can be used as a reference such as the data from an existing well, and *(e)* regulatory constraints. These factors were considered in structuring the CTS survey and associated survey lines, outlined below.

4.1.1 Survey Design

In view of these various considerations, the basic strategy for the CTS involves aerial EM, Gravitometric, GPR, and Video surveys which will be followed with the ground-based surveys of specific areas. The ground-based surveys will include Seismic, Resistivity, Magnetotellurics, GPR, Surface EM, VETEM, Gravitometric, and Neutron Imaging. Moreover, the 3D Seismic, GPR, High Resolution Resistivity, and Neutron Imaging will be used for AOCs and other areas which may warrant such investigation based on the results of 2D surveys.

4.1.2 Survey Lines

Exhibit 4.1.2-1 shows some planned survey lines superposed on a map of the CTS. They include survey lines for 2D and 3D surveys with the ground-based GPR, High Resolution Seismics, Resistivity, and Neutron Imaging (specific areas) but, however, does not include gridlines for both the aerial and other ground-based surveys planned. The latter will be included in a detailed survey plan at the start of the next phase when permitting and license requirements, if any, are clarified. The GPR surveys are currently planned at frequencies of 80, 225, 450, and 900 MHz. For the advanced GPR, the same survey lines will be used; except that frequency selection would depend on the equipment selected and available (AES, Systems & Software) for simple modification to generate in-the-field-crafted-and-coded waveforms / pulses, discussed in **Section 3.0.** However, the frequency selection can and will probably be expanded or altered to include other frequencies, both higher and lower, as the results of both the limited resistivity surveys of the CTS conducted on December 16, 1995 are fully analyzed and the laboratory measurements on the RF properties of the soil samples obtained from the CTS are completed. The preliminary results of the limited resistivity survey at the CTS are presented later in this section.

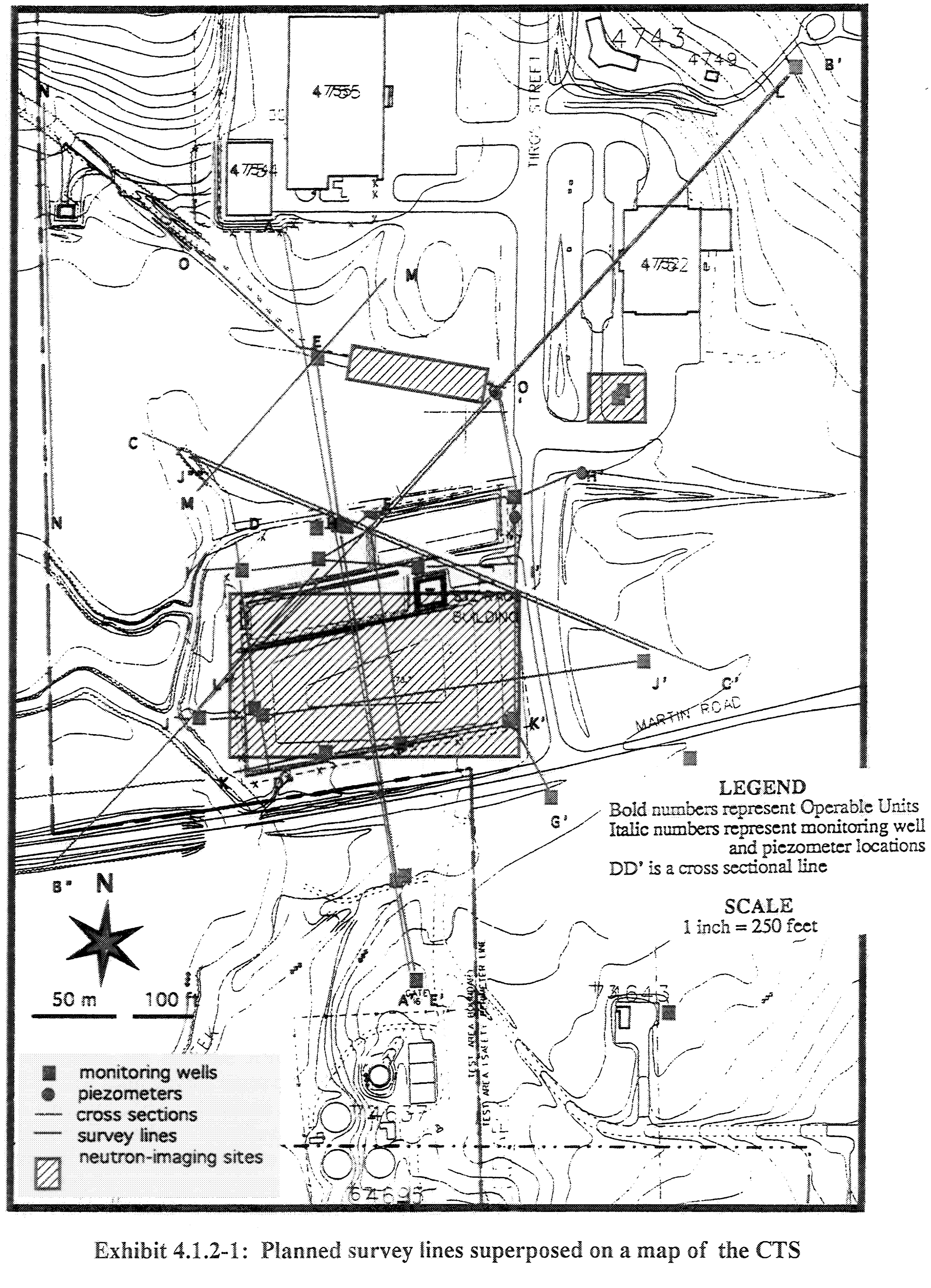

Exhibit 4.1.2-1: Planned survey lines superposed on a map of the CTS

The 2D surveys will consist of a single transect varying in length from 200 to 600 m. These lines must be long enough to provide an idea of the structure of the bedrock and the location of the water table. Transects should be oriented so they are parallel to the strike and dip of the bedrock because they represent the directions along which structure changes and the third dimension is assumed to be relatively constant. The 3D surveys are composed of a series of closely-spaced parallel lines. They are usually more time-consuming to complete, and thus need to be generally limited to surveys of relatively smaller areas. However, they provide highly detailed images of the subsurface which are useful in identifying small-scale anomalies. The extent of 3D surveys that is most useful to meeting the objectives of a survey is best determined during the survey itself as results of aerial and other 2D surveys become available.

Both the 2D and 3D survey sites are constrained by several factors. The most significant criterion in selecting sites is proximity to existing boreholes and monitoring wells. GPR will be used to provide a continuous transect between subsurface data points. Borehole information can be used to fine-tune GPR depth information while GPR provides the spatial coverage not possible with one dimensional surveys.

All 2D lines connect several boreholes and pass through mostly cleared and level terrain. Lines EE and DD follow the strike and dip respectively of the bedrock while FF goes along the dip of the water table.

Assuming a line spacing of 0.1 - 0.2 m, approximately 5 kilometers of line will be traversed for site 1 and 3.8 km of line for site 2. Wherever feasible, 2D and 3D surveys will be performed concurrently at various frequencies thereby significantly reducing on-site operating time.

4.2 Management Plan

The overall management of the CTS survey will be the responsibility of an ECG Project Manager (PM), located at the CTS site from the initiation of the survey. The PM will be responsible for the coordination, management and control of all survey activities that will include:

* Development and implementation of all required Plans including the Health and Safety Program (H&SP).
* Security and Badging Plan.
* Oversight and coordination of the acquisition of any and all required permits and licenses as discussed in **Section 3.0.**
* Coordination of all survey activities with the cognizant groups and agencies at the NASA MSFC and Redstone Arsenal, and with all appropriate Federal and State agencies with jurisdiction and concerns. This includes obtaining clearances in advance for any aerial survey efforts from the Range Safety Office at Redstone Arsenal, and the Communications Spectrum Managers at MICOM and NASA.
* Specifications and procurement of service subcontracts for specific survey modalities.
* Planning, management and implementation of data interfaces and integration of survey data and findings with the NASA MSFC Information Management System.
* Management and reporting including financial control and subcontract management.

4.2.1 Agency Contacts

Exhibit 4.2.1-1 represents the minimum list of agencies and persons that will be contacted prior to and, asappropriate, during the CTS subsurface characterization study. Other persons and agencies will be contacted as the need is identified.

Agency/Office	Point-of-Contact	Phone No.
NASA MSFC		
Environmental Office	Greg Burns	(205) 544-5214
Safety Office	Vyga Kulpa	(205) 544-1383
Primary Spectrum Manager	Muse Mann	(205) 544-0140
Industrial Hygiene Office	John Noblin	(205) 544-5738
USA MICOM		
Spectrum Manager (Coordination)	Dave Smith	(205) 876-1688
Redstone Test & Training Center		
Safety Office, Test Range Clearances	Jim Gibson	(205) 842-6620
Environmental Mgmt/ Planning Office, BioInvestigator, Site Analysis/Mgmt, and Wetland Surveys		
Ecologist	Susan Weber	(205) 876-3977
Biologist	Danny Dunn	(205) 955-6970
Geologist	Whit Walker	(205) 955-4653
U.S. Fish & Wildlife Service		
Biologist	Gary Phillips	(334) 285-9600
Alabama Department of Environmental Management		
General, Air, Water, Solid Waste	Jimmy Coles	(334) 271-7700
Water Quality Permits	James McIndoe	(334) 271-7826
Groundwater Permits	Sonya Massey	(334) 270-5655
Alabama State Game & Fish Agency		
Game Warden	Capt. Steve Pepper	(205) 353-2634, 2637 (205) 233-1609
Game Warden	Larry Allison	(205) 890-0277
Biologist	Brewer Dewey	(205) 379-4653

Exhibit 4.2.1-1: List of Agencies to be Contacted

Agency contacts, outside NASA, will be required only if invasive sampling methods are used that conflict with the regulatory requirements such as for the wetlands, including the channel of Indian Creek, or the spring in the NW portion of the CTS. Nothing that will be done during non-invasive sampling is expected to pose any threat to any sensitive or other wildlife species. However, courtesy notifications to the Alabama Game & Fish Agency (AGF) and the USFWS should be provided prior to beginning and during the survey. The ADEM will be notified well in advance of any survey activities to be undertaken both as a courtesy and to ascertain that all permitting requirements are being met. Similarly, Redstone Arsenal's Natural Resources Management Group and the NASA MSFC Environmental Group will need to kept informed of all survey activities, both planned and accomplished.

4.2.2 H&SP

ECG has a Corporate wide H&SP to protect employees and personnel involved in working in potentially risky environments. This H&SP, incorporated in ECG's Policies and Procedures Manual, encompasses ECG's policies, procedures, standards, and guidelines for the development of a specific project-based H&SP and practices both in and out of the field. Of course, any such plan shall include amendments necessitated by the H&SP requirements of NASA MSFC and Redstone Arsenal.

It will be necessary to implement a Subsurface Site Characterization Survey H&SP at the beginning of Phase II. This document will be in conformance with the requirements contained in the following NASA MSFC documents:

- DRD No. STD/SA-SHP; Safety and Health Plan
- NASA Safety Policy Document NHB 1700.1(VI-B), Chapter 2
- Management Instruction, MMI 1710.1G, Safety Review and Approval of Hazardous and Potentially Hazardous Facilities and Activities at MSFC
- Management Instruction, MMI 1711.2E, Mishap Reporting and Investigation

This H&SP will also serve as an example to the CTS survey subcontractors in developing their respective H&SPs while allowing for the H&SP policies of subcontractors in as much as they meet the minimum requirements of the NASA MSFC and their representatives.

4.3 Implementation of Surveys

This section contains a brief description of diverse activities associated with the implementation of the indicated CTS survey. These activities cover a wide range from preliminary planning to evaluation, assessment and reporting of results.

4.3.1 Preliminary Planning

ECG reviewed the available historical and other background information on the CTS. The documents that were reviewed are enumerated in **Section 2**. However, prior to beginning the CTS survey, a review of all background data available up to that point in time should be accomplished to determine if any changes in the current findings and their impact on the CTS survey design need to be made. The current findings of the review of the CTS site is summarized below.

4.3.1.1 Background Information Review

Sensitive Species & Habitats:

The proposed CTS contains areas of hardwood forest, open, treeless areas that are mechanically mowed at regular intervals, and a small stream. There lies a jurisdictional wetland along the stream which is a tributary to Indian Creek. The wetland is classified as palustrine, forested (MSFC Wetlands Map). The soils on the CTS are predominantly of the Decatur-Cumberland-Abernathy and Huntington-Talbot-Colbert associations and the land cover form is deciduous forest (NASA MSFC Land Cover Form Map, Ref. 4).

The CTS may contain habitat for sensitive species. The stream may provide habitat for either the Slackwater Darter (*Etheostoma boshungi*) (Federal Threatened) or the Tuscumbia Darter (*E. tuscumbia*) (State Species of Concern) or both species. The forested areas of the CTS might provide foraging habitat for Cooper's Hawk (*Accipiter cooperi*) (State Species of Concern). Nearby caves and the forested areas on the CTS may provide foraging habitat for three Bat species, the Gray Myotis (*Myotis grisescens*, Federal, Alabama Endangered), the Indiana Bat (*M. sodalis*, Federal, Alabama Endangered), and Rafinesque's Big-Eared Bat (*Plecotus rafinesquii*, State Species of Concern). In addition, solution cavities underlying portions of the CTS are thought to contain Alabama Cave Shrimp (*Palaemonias alabamae*, Federal Endangered) (NASA MSFC, Pers Comm). The USFWS have expressed concerns that soil disturbing activities along Indian Creek could increase siltation of the stream with subsequent degradation of habitat in the stream. They recommend avoidance of soil disturbing activities or mitigation by silt trapping if avoidance is impossible. The USFWS has also expressed concern over activities that could increase silt load into the Tennessee River which contains several sensitive Mussels.

There appears to be no reason for concern for any adverse impact on the site's environment or sensitive species as a result of the proposed surveys. The surveys will not cause any activities that are fundamentally different from the current normal activities at the CTS. Potential impact to fish and other aquatic organisms will be avoided by not using invasive survey techniques, especially in the wetland or near the stream or other surface water. Aerial surveys should not have any impact on bats or birds that differ from normal flight operations at the facility. There is no expectation of working in habitats that might be occupied by any other sensitive species known to occur on the facility.

4.3.1.2 Results of Initial CTS Visit

The CTS was initially visited in September, 1995. Representatives of the ECG team reconnoitered the area and walked around in the, then dry, wetland. The observations made during the site visit have been discussed in **Section 3.0.** A summary of the important site features relevant to reconsideration during the implementation of the CTS survey is presented below. No serious impact of these features is anticipated on the conduct of the planned surveys.

Wetlands Access:

The wetlands portion of the CTS appears to be the only area where vehicular and, hence, equipment access will be a problem. There is a raised dirt road into the wetland, but no apparent lateral roadway. There are some areas along the road where the forest is relatively more open, providing potential locations for small vehicle or equipment access without requiring vegetation removal or major surface disturbance.

Sensitivity To Disturbance:

Because of the U.S. Army CoE jurisdictional status of the wetland, there may be agency concerns relative to ground- disturbing activities, alteration of water flow patterns, and removal or severe disturbance of vegetative cover.

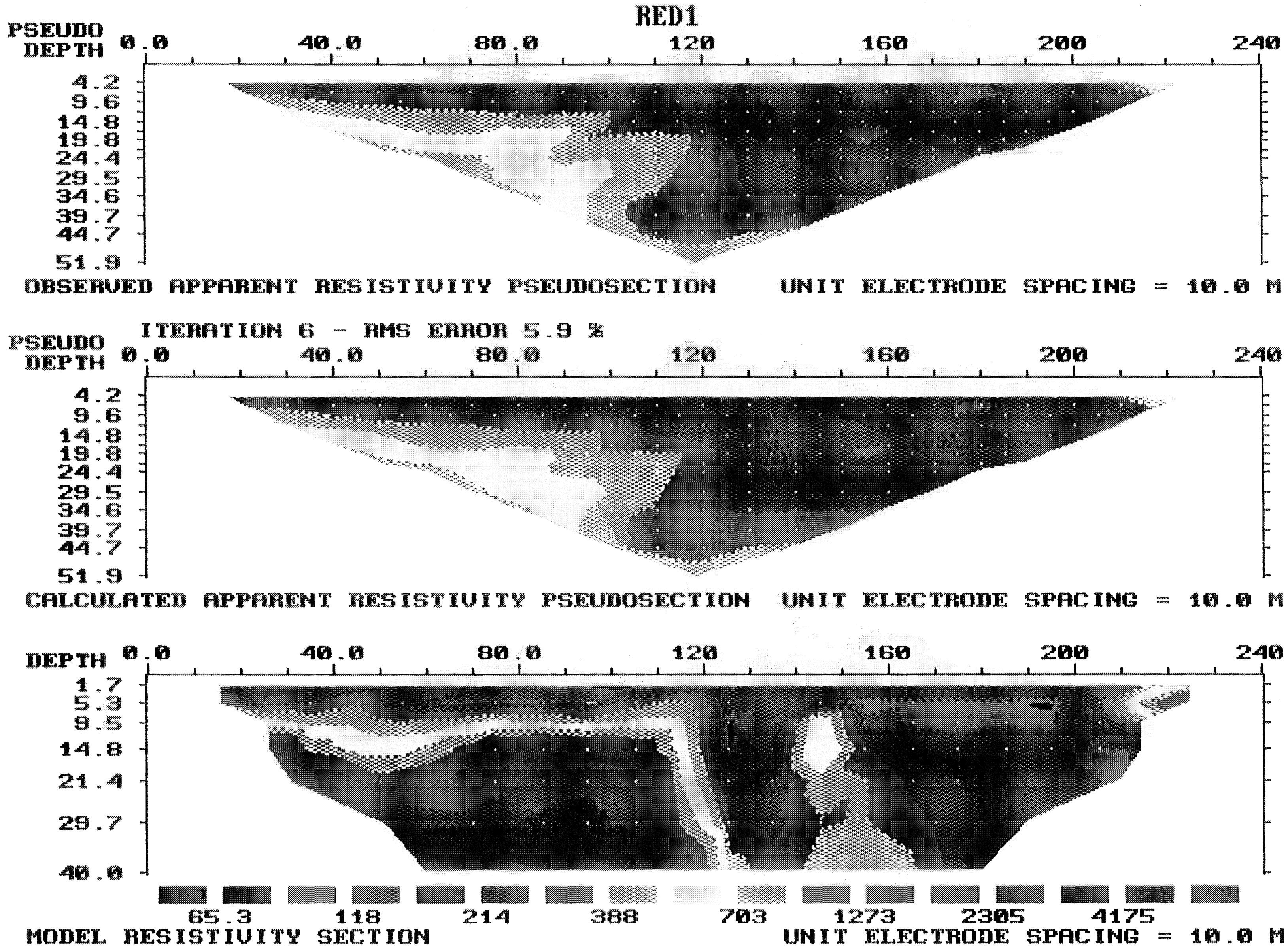

Exhibit 4.3.1.3-2: Results of the limited Resistivity Surveys

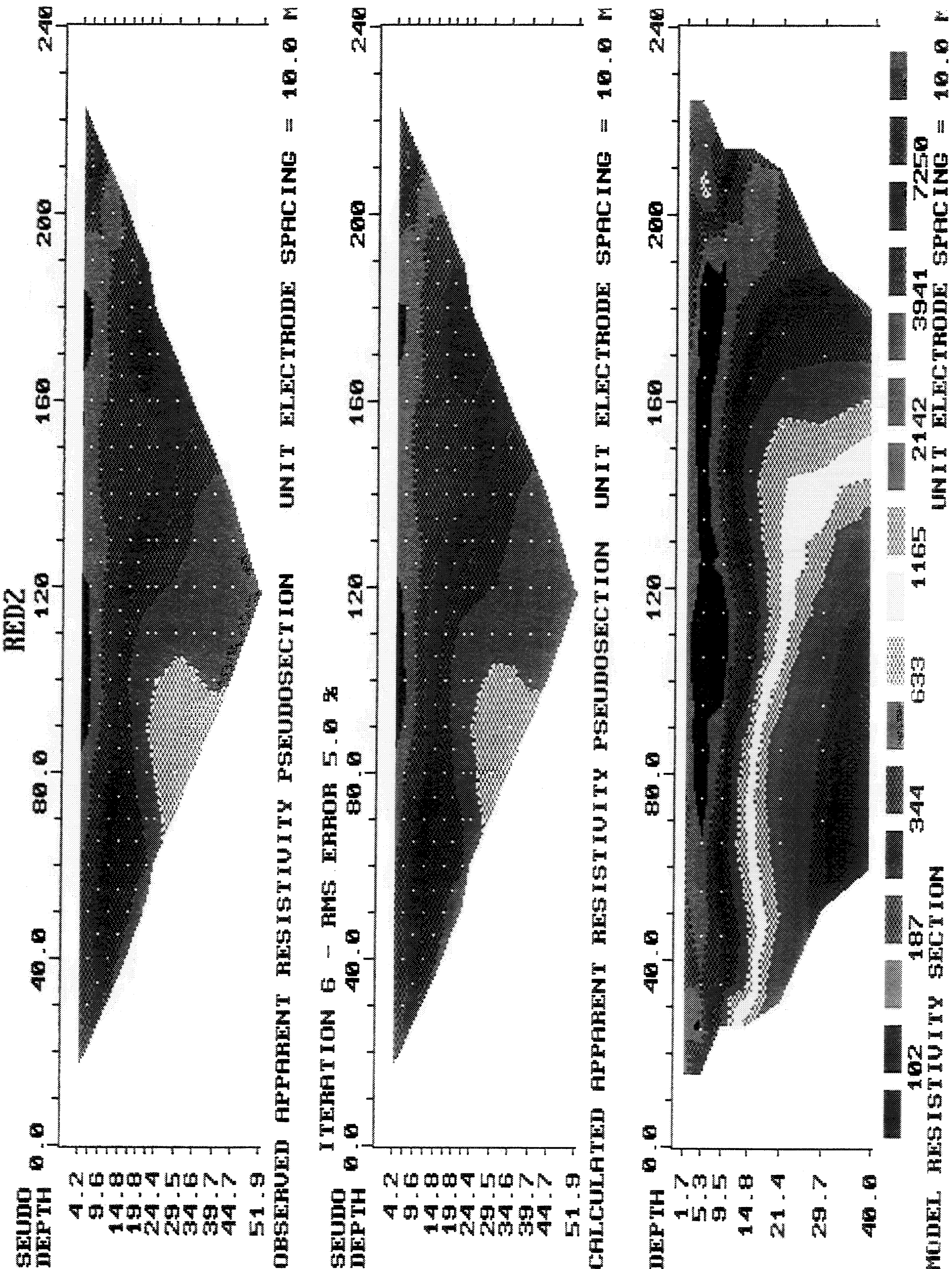

Exhibit 4.3.1.3-3: Results of the limited Resistivity Surveys (Continued)

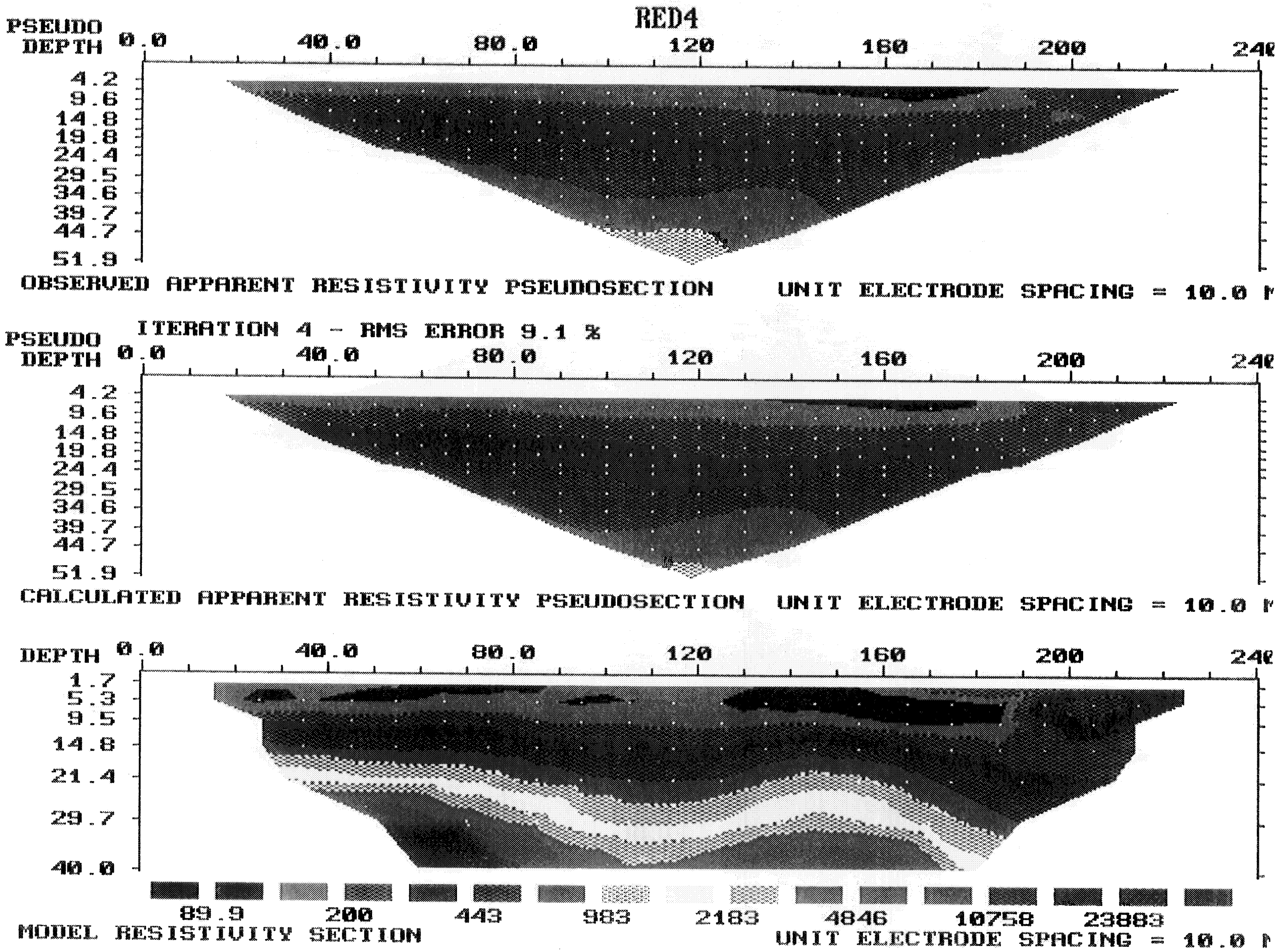

Exhibit 4.3.1.3-5: Results of the limited Resistivity Surveys (Continued)

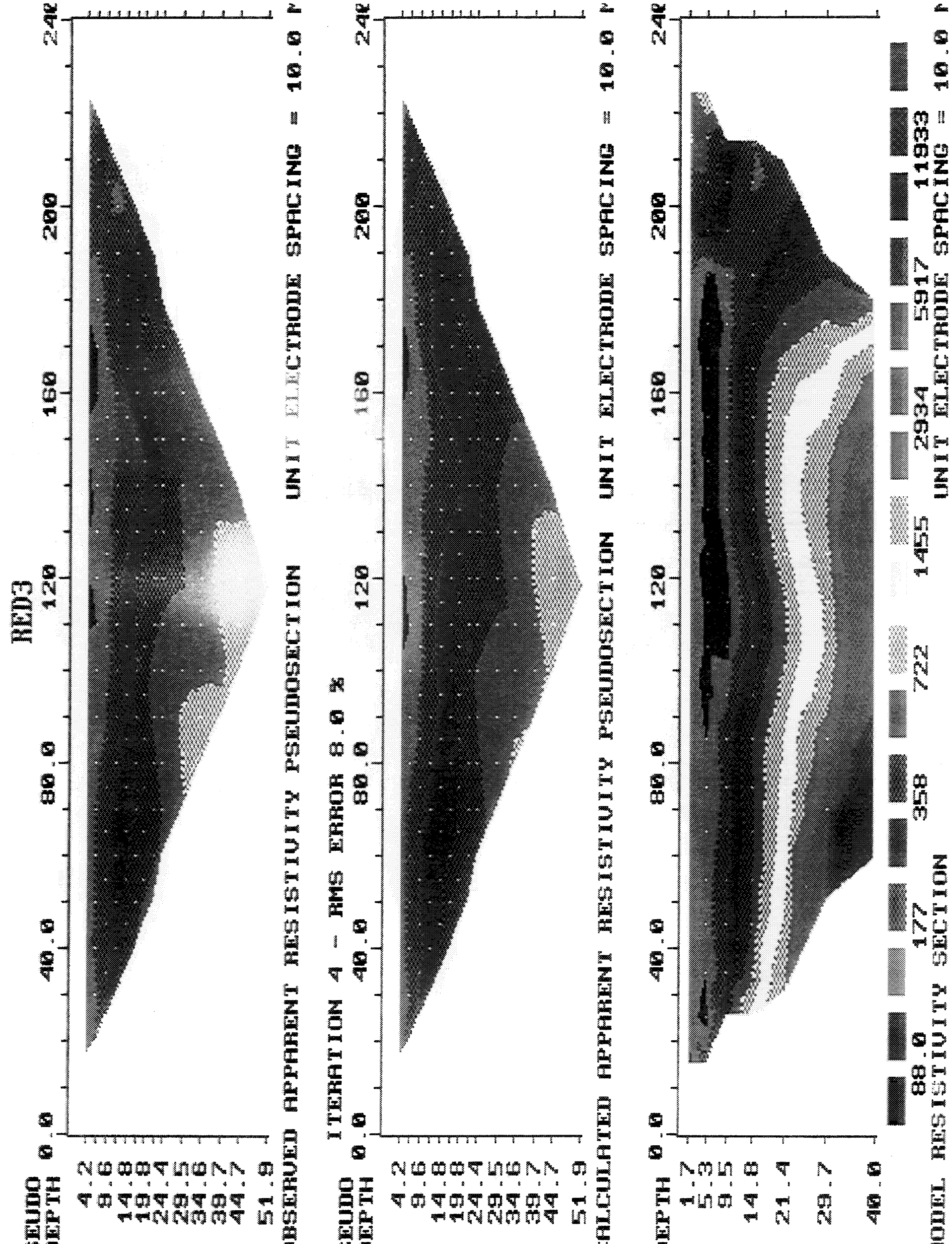

Exhibit 4.3.1.3-4: Results of the limited Resistivity Surveys (Continued)

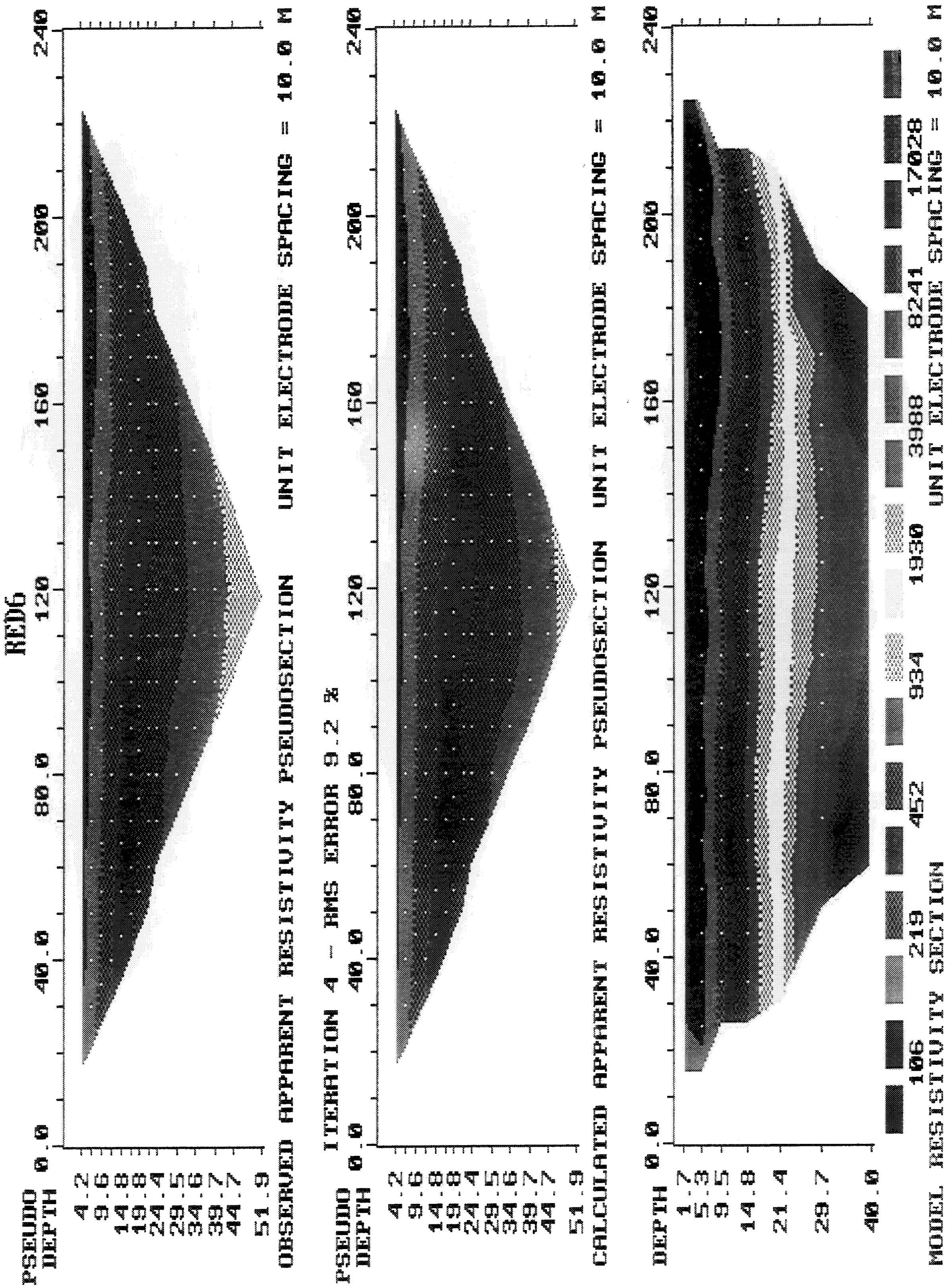

Exhibit 4.3.1.3-7: Results of the limited Resistivity Surveys (Continued)

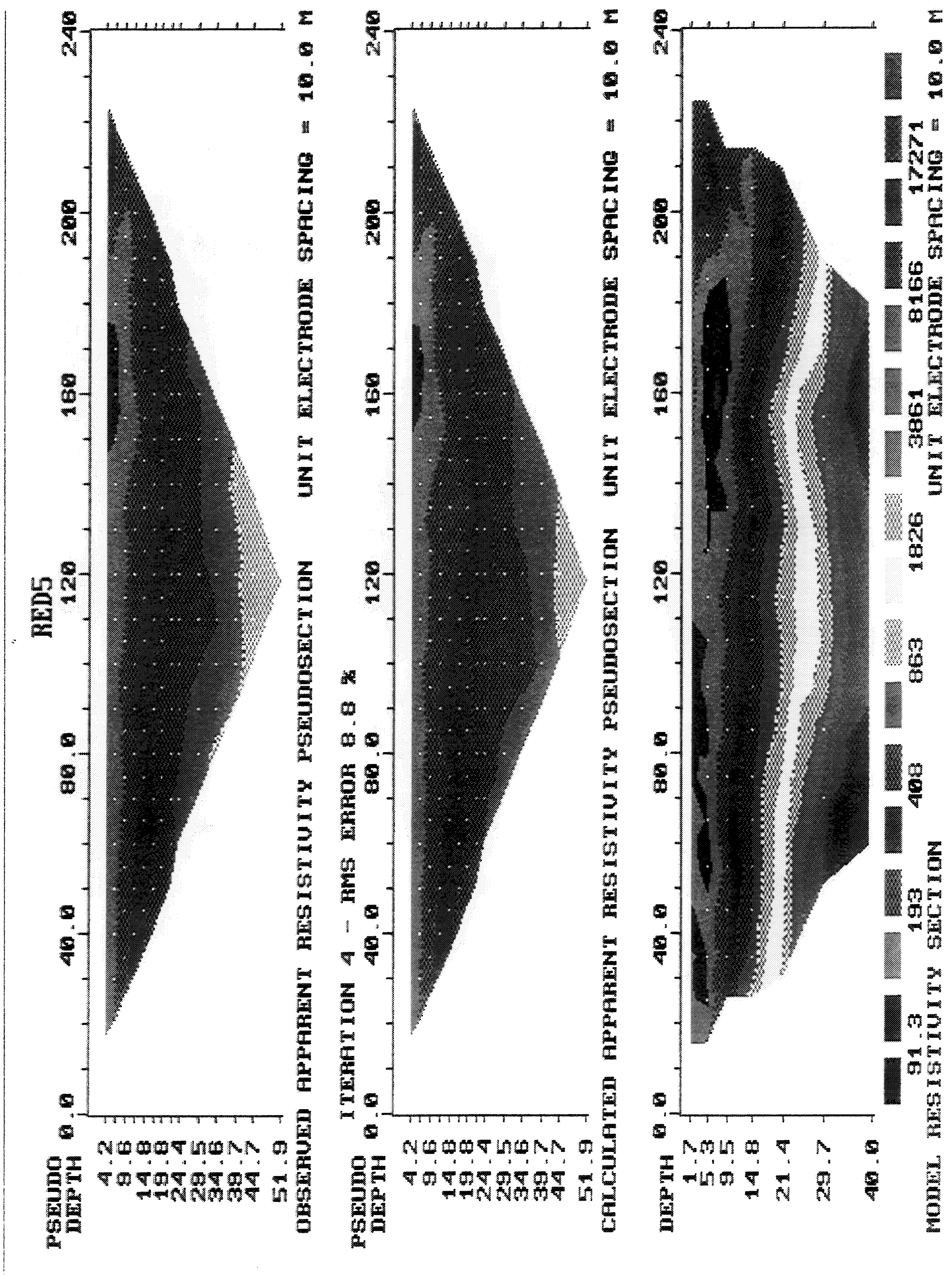

Exhibit 4.3.1.3-6: Results of the limited Resistivity Surveys (Continued)

Any such activities in the wetland will require a Section 404 permit from the U.S. Army CoE and possibly permits or oversight by the Alabama Department of Conservation and Natural Resources. However, none of these is likely to be necessary since the focus of the CTS survey is on non-invasive methods.

Access by Equipment:

Any equipment required to be used within the wetland will have to enter via the existing roads. Location of grid positions within the wetlands and off the road will require that the equipment be either hand-carried or be capable of being pulled or carried in by a small vehicle, *i.e.*, a balloon-tired-ATV, that will have little or no surface impact and will not require vegetation removal

Wet Soil Conditions:

During much of the year, the wetlands will be either partially flooded or the soil will be at or near saturation. Under these conditions, access off the existing road may be difficult or cause sufficient surface perturbation as to be of concern to the U.S. Army CoE. Thus, all surface sampling should be scheduled during periods when soil moisture is acceptable.

4.3.1.3 Results of Limited Resistivity Surveys

Samples for laboratory measurements of the RF characteristics of the CTS soils were taken during the site visit. Results of these measurements are not available at this time. Additionally, consideration for highly limited Resistivity and EM surveys of the CTS to obtain data on some soil properties. Although those limited surveys were not within the scope of the Phase I contract, ECG was able to perform Resistivity and EM surveys of a very small part of the CTS on December 16, 1995. The data collected as a result of these highly limited surveys have not yet been fully evaluated. Some initial results from these Resistivity measurements are shown below.

Exhibit 4.3.1.3-1 below shows the six survey lines and their orientation to the site where resistivity data was acquired during a limited survey of the CTS on December 16, 1995. Each line, with an interline separation of 20 ft (about 7 m), used 25 electrodes and a 10 foot (about 3 m) spacing between the electrodes.

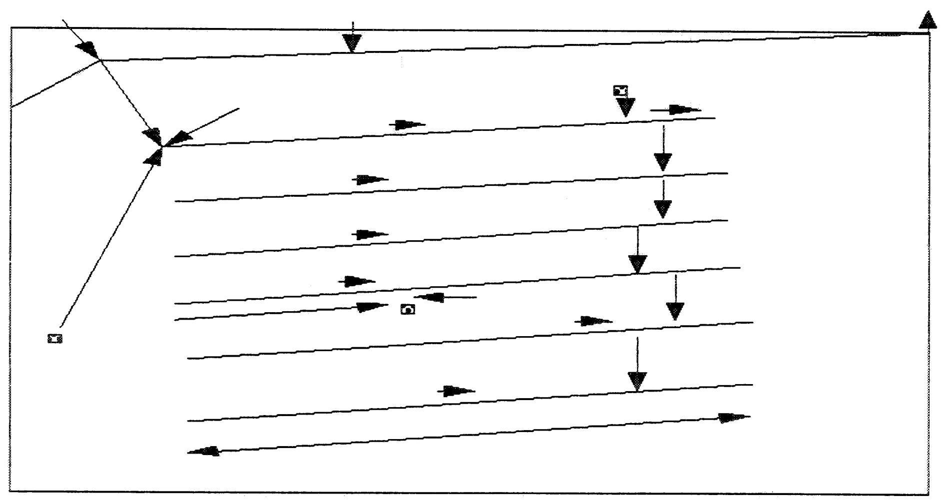

Exhibit 4.3.1.3-1: Resistivity Survey at MSFC at the NW Corner of the Fenced Area

The results of these limited Resistivity Surveys are presented in **Exhibits 4.3.1.3-2** through **4.3.1.3-7**, labeled as RED 1 through RED 6 corresponding to the lines in **Exhibit 4.3.1.3-1.** In these exhibits, the X-axis is oriented along the survey line and the Y-axis beneath the ground. The top display is the raw apparent resistivity data and the middle display is the model's version of the raw data set after a variable number of reiterations. The bottom display is the modeled resistivity profile in Ohm-Feet (that is just the way the scaling works out).

The first line is most interesting since it was run parallel and about 10 feet (about 3 m) away from the existing line of some wells. Note the high resistivity feature toward the left side extending toward the surface which usually indicates limestone caves and/or and sinkholes. The one boring that reportedly hit a cavity and brought water to the surface is very close to the high resistivity feature. The well that was installed to the east about 15 feet (about 5 m) had no contact with the cave.

As one moves across the site and observes the other five lines, a rather drastic change occurs in a very small space (100 ft). At RED 6, the model shows a classic layered earth model. This area was at the low portion of the site and water was standing at many places along a line. The conductive clay cap is clearly shown. This Resistivity Survey was performed almost under ideal soil conditions. The soil was wet and thus conductive; the rain had occurred just the night before. The high and low resistivity areas were clearly seen. Under relatively drier weather conditions, the GPR surveys could have revealed not only the features revealed by the resistivity method but also with higher resolution, thereby allowing for the development of a more resolved model of subsurface contaminant migration.

4.3.1.4 Preliminary Sampling Plan

A preliminary sampling plan for the CTS survey has been structured which may, however, require some modifications when the CTS survey is authorized. The sampling plan obviously needs to be sensitive to the suite of characteristics of the CTS and sensor modalities selected because they together influence the choice of sampling (survey) design and survey time lines. The sampling plan includes:

Scheduling of Methods with the Best Chance of Providing Usable Results:

Several known technologies appear to have operating features that optimally match with the characteristics of the CTS and the survey objectives. Thus, the selected modalities have to be scheduled when they can best yield the results for which such sensor modalities were selected. The limited resistivity data presents an example where the timing of such a survey was essentially ideal..

Equipment Platforms Best Adapted to the CTS:

The most appropriate platform for the aerial survey of the CTS will be a helicopter. The area to be surveyed is relatively small and Helicopter surveys are economical for small areas and are compatible with FAA regulations in most places. ground surveys will have to be accomplished by portable or man carried equipment. A differential GPS system is expected to be required for the ground-based surveys.

Structures And Activities at the CTS:

The CTS has on it numerous structures and routine usage activities. These factors are important to the scheduling of different surveys. It may be difficult to use certain sensor modalities when they interfere with normal activities on the site or when people are within the buildings. Thus, it may be necessary to schedule such surveys during periods when usage is minimum or potential interference from other activities is minimal.

Another feature that would require further assessment prior to conducting the CTS survey is the Redstone Army Airfield located in the Northwestern section of the Arsenal, about 1.5 km from the Northern border of the CTS. Instrument approaches are available from either direction using a Non-Directional Beacon (NDB) or a Very-High-Frequency Omni-Range (VOR) station approach. There may be interference from this navigational radar so it may be required that NDB be used during surveying. In this case, it is recommended that NDB be used during the time of surveying rather than VOR.

Agency Contacts Required:

Potential agency contacts for purposes of obtaining permits or licenses or for notification of survey activities are presented in **Section 4.2.** No other agency contacts are anticipated. If either the use of invasive sampling or a need to put in roads or move significant amounts of soil within the wetland area or within 15 m (50 ft) of a stream channel or spring becomes necessary, a U.S. Army CoE Section 404 Permit will be required. If a 404 permit is needed, it is anticipated that the project will qualify for a "Nationwide Permit" because any disturbance to the site is not expected to cover more than five acres of ground. Application to the U.S. Army CoE will be initiated at least 120 days prior to anticipated sampling, and sooner if possible. Discussions with the Federal and State Wildlife Management Agencies will be required as part of the U.S. Army CoE 404 permit process.

4.3.1.5 Security / Badging

All field personnel working on the project will require appropriate badging and clearance for the facility. NASA security will be contacted in advance of undertaking any survey activity and badging obtained as appropriate for access of various personnel and subcontractors.

4.3.1.6 Safety Requirements and Training

A H&SP will be developed and implemented, as discussed in **Section 4.2**. This H&SP will meet or exceed all the NASA MSFC Safety and Health requirements. All subcontractors will be required to adhere to the H&SP.

4.3.1.7 Permits / Licenses

At this time, no requirements for special permits and / or licenses is evident, the survey contractor should be vigilant to any such requirements when the detailed survey and implementation approachs for all sections of the CTS are finalized prior to accomplishing the survey. In any case, the various agencies and groups listed in **Section 4.2** will be contacted at project initiation to determine what permits may be required and what the procedures will be to obtain those permits. As appropriate, permitting activities will be initiated at the earliest opportunity.

4.3.1.8 Equipment / Personnel Deployment to CTS

In general, it will be the responsibility of each survey modality contractor/subcontractor to arrange for acquisition, transportation, storage, staging, site preparation and on-site facilities for the hardware and personnel required. The CTS survey PM will be responsible for establishing the mechanisms for the contractor / subcontractor to use and to apprise them of known constraints and timing of their individual efforts. The PM will not only coordinate requirements for site preparation and staging with the appropriate NASA personnel and the survey modality contractor / subcontractor but will also oversee the conduct and performance of all surveys to ensure that compliance with all performance and regulatory requirements and specifications are met.

In order to minimize impacts of the project to ongoing NASA and the U.S. Army activities at Redstone Arsenal, it is recommended that a trailer with utilities and sanitary facilities be located on the CTS. All personnel involved in the particular survey(s) would use the trailer as a base-of-operations during their tenure on the CTS. To the extent practicable, equipment staging and storage areas should be on or near the CTS.

4.3.1.9 Survey Locations

Survey locations are shown in **Section 4.1.2.** They will be re-examined and modified, if necessary, as the detailed planning and implementation of the CTS survey is initiated.

4.3.1.10 Survey Timelines

Upon receipt of authority to proceed with the CTS survey, the Project PM will contact the persons and offices listed in **Section 4.2**, **Exhibit 4.2.1-1**. All necessary planning, mobilization, and coordination activities will be initiated. Survey schedules will be firmed up to the extent possible at that time. All survey scheduling will be adjusted so as to avoid interference with any ongoing NASA or U.S. Army operations at Redstone Arsenal. Survey activities will be scheduled to take advantage of " the most appropriate time windows" available over the duration of the survey. Within the anticipated time window, unexpected delays could occur, but scheduling will remain as tight as possible. A preliminary survey schedule is presented in **Exhibit 4.3.1.10-1.**

4.3.1.11 Implementation of Sampling Grids and Protocols in Place

When all appropriate contacts have been made and scheduling / use conflicts adjusted, the survey grids and flight vectors will be laid out. The precise location and extent of some of the sampling locations / grids will depend upon the results of the aerial surveys. AOCs and "hotspots" that appear as a result of airborne surveys and / or other background information will be shown on the site map as areas for detailed sampling by appropriate ground-based technologies. These latter surveys will also be closely coordinated with the appropriate personnel at the NASA MSFC and Redstone Arsenal.

Some sampling will be performed in close proximity to, as well as inside, some of the existing monitoring wells. Use of the wells and sampling technologies will be coordinated with the appropriate NASA MSFC environmental staff. It is anticipated that existing data from those wells will be used to calibrate the sampling technologies used.

4.3.1.12 Relationship of Validation Test Wells with Known Locations of Contaminant Sources, Local Site Conditions, and Preferred Locations for Other Test Modalities

An important part of each survey technology is the need to calibrate the equipment and technique to well accepted references including information from the particulars of the CTS. For each survey modality, some effort will be initially used to on-site, real-time design, reference selection / location, and calibrations. Initial data from many of the surveys will provide new information that can be used to refine and improve subsequent data. Unexpected information may result in modification of survey protocols that benefit a specific survey or a group of survey modalities. The existing monitoring wells at the CTS are candidates for use as references and modality calibrations.

The wells preferred for use during this project will be those that provide a range of known conditions for purposes of calibration of different sensor modalities. Ideally, the wells will be available to sample known contaminant plumes and areas known to be uncontaminated. The wells should also allow sampling of the range of known subsurface environmental conditions.

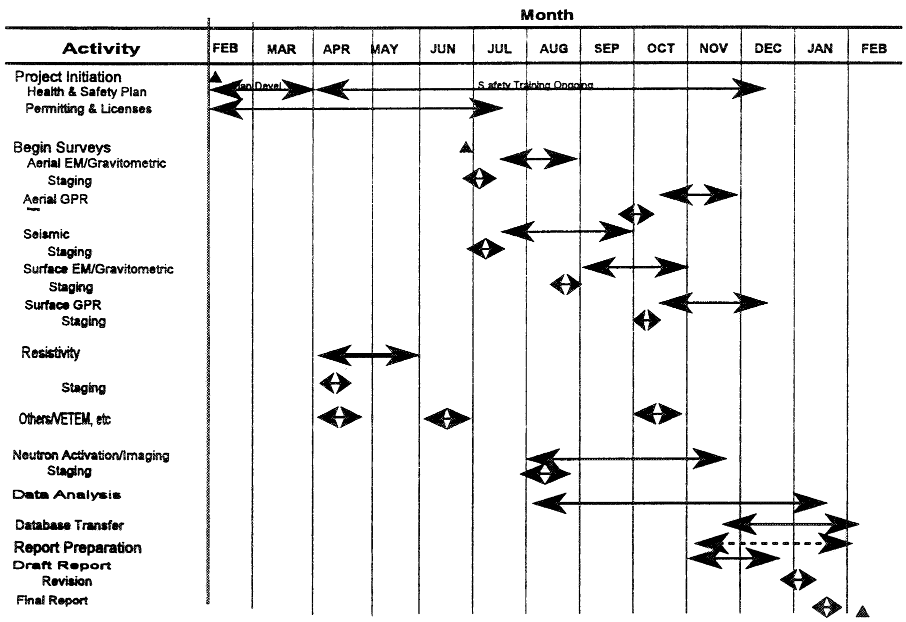

Exhibit 4.3.1.10-1: Preliminary Survey Schedule for the CTS Survey

4.3.1.13 Survey Procedures and Schedule

Exhibit 4.3.1.10-1 shows the anticipated survey schedule and modalities for the CTS Survey. This schedule is preliminary and may, depending on environmental conditions and unforseen delays, be modified as the survey is implemented. Start and end times are shown to the approximate quarter of the month. Within the indicated time lines the various contractors will come onto the CTS and, depending on environmental conditions, perform their portions of the survey effort. Data analysis will be an on-going part of the project.

4.3.1.14 Data Collection, Analysis, Management, Integration and Display Protocols

Each survey subcontractor will be responsible for data collection and analysis for the existing modality used. For advanced modalities, the ECG Team will perform data collection and analysis. All data fusion, integration, display, and detailed interpretation will be accomplished by the ECG Team in consultations with the NASA MSFC Environmental Directorate. Data collection, analysis, integration, interpretation and display methods, discussed in **Section 3.0**, particularly for advanced sensor modalities, will be used.

4.4 Potential for Utilization of Automated Survey Equipment at the CTS

The potential to automate many of the survey procedures exists. However, the survey services contractors tend to specialize in a specific modality or modalities and have yet to provide automation as part of their practice for geophysical surveys. This is in large part due to the initial investment involved in automation which the typical geophysical surveyor, generally being a small company, has not been able to afford. As environmental survey requirements increase and integrated, multi-modal surveys are performed, investment in automation of survey methods could become attractive. However, for the CTS, automation of survey methods is premature.

Section 5
Cost and Benefit Analysis

In **Section 3.0**, a variety of sensor modalities for geophysical surveys are presented. Such surveys can be performed by use of airborne- and/ or ground-based sensors. The choice of mix among these modalities depends on a number of complex factors that range from the survey requirements to site conditions. Geophysical survey modalities not only provide widely different information with regard to the type, content, and quality but they also differ in costs, ranging from a few hundred dollars per acre to over $10,000 per acre. Cost estimates for different survey modalities as well as an example integrated survey, involving airborne surveys and limited-area ground-based surveys, are presented in **Section 3.6.** Thus, in this section, we only discuss collateral benefits that can be derived from other "value-added" uses of recommended geophysical survey techniques mobilized to support solutions to subsurface environmental problems.

The sensors used for geophysical surveys are also the ones that are directly relevant to a number of other applications that include mapping and location of UXOs, buried man-made objects like tanks, toxic and hazardous materials, utility lines, underground operations, archaeological artifacts, and others. It is not simple to put a value on any of these applications because the price and value are high when one needs to solve a problem but certainly not so if any of that information is generated as a by-product of a geophysical survey conducted with a different goal. If a survey for one of these collateral applications were specifically commissioned its cost would not be much different than that for a typical geophysical survey. Otherwise, the value of the ancillary findings would be what one can obtain from its sale to an interested party. However, if coordination of a planned geophysical survey is made in advance with the other interested party (ies), the best value may be derived not only for the ancillary information but by the primary party as well. Such coordination is possible between different agencies of the government, particularly if they have operations on adjacent sites or within the same general complex. Where transfer and / or development of a near-ready technology is involved to expand or enhance the performance of surveys, joint participation between the interested agencies can be a distinct possibility.

Consider now a geophysical survey of the subsurface underlying the NASA / MSFC which is located in the same complex as Redstone Arsenal of the U.S. Army. Over the decades, the NASA MSFC and the Army have carried out operations at this site that have significant parallels between their many activities. Thus what may be mapped or imaged at the site underlying the MSFC may well be of some interest to the Army or the same techniques can be readily applied to survey the site underlying the rest of Redstone Arsenal. Survey costs and strategy would depend on, among other things, goals of the survey, the acreage of the survey site, and site conditions if they are significantly different. If sites occupied by both the MSFC and the Army at Redstone Arsenal can be surveyed at the same time, significant cost savings can be realized, at least, in the areas of planning, staging, implementation, data processing and interpretation, performance of the airborne part of the survey (a rectangular survey pattern with large length / width ratio is easier), and other activities encompassing a survey. While it is difficult to quote a specific percentage in cost savings under the scenario just stipulated, savings upto 20 percent or more are conceivable. The actual cost to each of the two parties could be 80 percent or less of what it would cost if the two had their sites surveyed independently.

Section 6
Results and Recommendations

Numerous airborne and terrestrial technologies exist for non-invasive mapping and characterization of geological, hydrogeological and chemical contaminant features of the subsurface. Both traditional and emerging technologies have been assessed. Not only are they available or essentially available but are also found to be relevant to the requirements of the NASA MSFC. In the arsenal of technologies selected and recommended for use at the MSFC, certain emerging technologies have been included that can potentially provide *(1)* larger penetration into the subsurface, *(2)* higher resolution with the capability to detect and discriminate targets of interest, *(3)* reduced need for the professional expertise, including geophysicists, for the interpretation of results, and *(4)* a capability for in-situ profiling of chemical contaminants, not just in the locale of, but within a volume of 2 to 3 meters in diameter around the target point. These advanced technologies, involving advanced GPRs and in-field Neutron Imaging are ready for field use and calibration and should be considered for pilot testing during the survey of the CTS, a site selected by the MSFC as a reference site where the relevant suite of geophysical sensor modalities can be assessed against "measures of success" stipulated by the MSFC. Moreover, very simple, low cost methods are outlined to validate the advanced concepts, both for advanced GPRs and related processing, and Neutron Imaging; accomplishment of such testing is recommended because of their unique potential in terms of the highly valuable information these advanced methods can yield.

An integrated survey strategy for survey of the CTS is recommended. The integrated approach would start with an analysis of the available historical and observational data. It would then be supplemented with overhead imagery, Helicopter EM / Magnetometry / Gravitometry, and Helicopter-borne GPR and Video Imaging. Identified AOCs would then be investigated with the productive versions of the ground-based sensors (Resistivity, EM, VETEM, GPRs, Seismic, Magnetotellurics, Gravitometry for example). Likewise, identified "hotspots" would be investigated with the more competent modalities to provide higher resolution of the subsurface features.

Neutron Imaging is recommended as an in-situ, confirmatory technique for the mapping of the presence of chlorine and heavy metals and possibly other elements such as nitrogen at the surface and near surface of the MSFC. The mapping of these elements should allow more precise location of the sources of different pollutants and allow to a more specific and less expensive remediation program. The recommended system hardware to conduct this survey is a portable probe consisting of a high resolution gamma ray detector (High efficiency High Purity Germanium detector), a small Deuterium-Tritium Accelerator tube providing a 14 MeV Neutron source (which provides maximum penetration in the formation, the broadest excitation potential for inelastic gamma rays, *e.g.*, the potential for the largest number of chemical species detection, and ease of manipulation while not in operation), and a portable fast and user friendly electronics and data acquisition system to allow for quick in-situ analysis of the data and portability during measurements. The deployment of the technique is recommended: *(1)* for well 28d, the only well on the CTS to have a sufficient diameter to use a Neutron Imaging tool, and *(2)* for selected surface as well as subsurface areas. The latter can be accomplished by use of a cone penetrometer housing the Neutron probe.

Finally, the collected and inverted data needs to be entered into a master GIS, where they would be fused with other geographic data, and visualized using computer-graphics techniques. One result of this strategy is that it provides the necessary information at the lowest possible cost; the other attribute is its flexibility for use at different sites.

The performance and cost of geophysical surveys can vary from site to site due to differences in site characteristics and the size and requirements of the survey. By design of an appropriate integrated survey, large geophysical surveys for characterization of the subsurface can be generally performed in sufficient detail and at an acceptable cost ($3,000 - $5,000 per acre). The actual cost would depend upon a variety of site related factors, extent of the AOCs, nature of the chemicals to be determined, and other constraints of a survey. The geophysical environmental surveys can be expected to become more cost-effective as survey service houses become vertically integrated to provide the total range of services as "One Stop" operations.

Volume II
Appendicies

Volume II
Appendix III-1

Subsurface Site Characterization Study
for
The National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

NASA MSFC Contract
NAS 8-40617

Volume II
Volume III-1
Subterranean Sensing with UltraShort Pulse Ground Penetrating Radar

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1. Introduction

The major advantages of RF sensing over, e.g., seismic sensing are:
(1) RF sensing permits directional sources.
(2) RF sensing permits remote, noncontacting sources as the dielectric impedance mismatch between free space and soil materials is 2-4 for RF impedances, but of the order of 100 for acoustic impedances.
(3) RF sensing antennas can be designed to have appropriate bandwidth and beam shape features.
However, the processing of RF sensor data has many similarities to the processing of seismic data, despite that in the case of RF sensing, *any* dielectric variation - not necessarily that due to a conductivity change - will produce reflections. Thus it is important to note the impossibility of distinguishing between σ' and $\omega\varepsilon''$ or ε' and σ''/ω without a molecular or atomic interpretation.

A rule of thumb for CW signals is that the attenuation of electromagnetic radiation rises with frequency and that at a given frequency wet materials exhibit a higher loss than dry ones. In the present instance, impulse, not CW, signals are addressed, and it is expected that there are major differences between CW, FMCW, stepped FM and impulse signals (Barrett, 1991). Unfortunately, the overwhelming amount of data on dielectric effects has been obtained with CW signals, so impulse effects with pulses shorter than the relaxation time of the material are seldom available.

To give a feel for the losses to be expected, some data - obtained with CW signals, *not short pulse signals* - are shown in the following Tables 1.1-1.3.

Table 1.1

	Frequency	Loss at constant wavelength
wet clay soil	100 MHz (single transit)	20-30 db m^{-1}
wet clay soil	1 GHz	100 db m^{-1}
sea water	100 MHz	200 db m^{-1}
sea water	1 GHz	300 db m^{-1}
fresh water	100 MHz	4 db m^{-1}
fresh water	1 GHz	40 db m^{-1}
ice, fresh water	1 GHz	1 db m^{-1}
ice, sea water	1 GHz	50 db m^{-1}
sandy soil	1 GHz	10 db m^{-1}
loamy soils	1 GHz	20-30 db m^{-1}
desert sand	1 GHz	1 db m^{-1}

Table 1.2	
	Permittivity at constant wavelength
water	80
most soils	2-6
soil-water mixtures	4-40

Table 1.3. (From Daniels et al, 1988)		
	Penetration depth	Maximum frequencies used
cold, pure, freshwater ice	10 km	10 MHz
higher temperature pure ice	1 km	2 MHz
saline ice	10 m	50 MHz
fresh water	100 m	100 MHz
sand (desert)	5 m	1 GHz
sandy soil	3 m	1 GHz
loam soil	3 m	500 MHz
clay soil	2 m	100 MHz
salt (dry)	1 km	250 MHz
coal	20 m	500 MHz
rocks	20 m	50 MHz
walls	0.3 m	10 GHz

Almost all subsurface radar systems presently operate at frequencies below 1 GHz as the attenuation increases with frequency. The conventional wisdom is that the earth acts as a low-pass filter. However, this conventional wisdom neglects two aspects of the problem: (i) soil is also a dispersive medium, and the low frequencies in the returned signal at the surface can either be due to low-pass filtering or medium dispersion; (ii) the relaxation times of the earth media are comparatively long (see Tables 4-6, below), therefore short pulse envelope effects may occur (Barrett, 1991, 1995a). The processing procedures proposed for Phase II will exploit the possibility of increased penetration using matching of the pulse to the media characteristics.

2. Subterranean Imaging with UltraShort Pulse Ground Penetrating Radar

2.1 Imaging Geological Strata

All discontinuities in subsurface geological maps are due to sharp changes in the dielectric properties of the medium. Imaging buried metallic objects is quite straightforward and the signal-to-noise can be increased by magnetic techniques which interact with the buried object and provide a stronger radar return, or, if the metallic object, e.g., a pipe, can be reached above ground, by conducting current along the pipe, which also provides a stronger radar return.

Literature abounds in diverse examples where the GPRs have been used for geophysical characterization over a wide frequency spectrum in the RF/microwave region. Many of these application examples are provided in Section 3.1 and Section 3.2 of volume I of this report. The examples of relevance to the UltraShort pulse GPRs are provided in Section 3.2. These examples were obtained with short pulse (1-5 nanosec. duration) ground penetrating radars, which used, however, nonoptimum (unmatched to medium) pulses.

The advantage of short pulse techniques, and even more so, of *optimized* short pulse techniques, is that not only is the medium penetrated and a radar return obtained, but *that return has maximum resolution of the subterranean strata and reflecting objects*.. Use of UltraShort crafted and coded pulses for GPR investigations of the subsurface can yield benefits that include higher resolution, higher penetration, detection and discrimination of targets at different depths, and interpretation of results without the use of professional expertise such as geophysicists.

3. System Subcomponents

A major task of Phase I is to identify optimum system components for Phase III. The following is a short appraisal of components presently available.

3.1 Antennas

A general problem with antenna designs is the obtainment of a balanced-to-unbalanced (balun) transmission line. A technique which is reported to work well is to use a sampling oscilloscope as a balun by employing two coaxial lines to the balanced antenna structure (Van Etten, 1977). The d.c. component of an impulse cannot be radiated, therefore the transmitted wave, i.e., the received wave for analysis, has equal areas above and below thE zero voltage axis. This waveshape is a differentiated impulse, doublet or monocycle. Furthermore, the transmitting transfer function of an antenna is the time derivative of the receiving transfer function of the same antenna. Two other requirements which are desirable (but can only be approximated) are (Van Etten, 1977):

(A) the antenna should have a flat frequency response; and

(B) the waveform should not distort as an antenna beam scans across a target, i.e., the requirement that the transmitting and receiving beamwidths are constant with frequency.

Yet in order to maintain a constant receiving beamwidth with frequency - i.e., in order to achieve (B) - the receiving aperture must vary with frequency - i.e., (A) cannot be achieved. Therefore, some engineering tradeoffs must always be made.

In the following, it is assumed that sufficient energy per pulse is available and does not impact the choice of a suitable set of antennas. However, if more energy per transmitted monocycle is required, then the *dispersive characteristics* of an antenna with a large time-bandwidth product (e.g, >3,000) can be used to achieve pulse compression. In this way, much greater energy per monocycle, or peak power, can be radiated. Advantage can also be taken of dispersion on receive. A major overall advantage of dispersive antennas is that they are more efficient than nondispersive. However, in the following it is assumed that sufficient energy per monocycle, or peak power, is available on transmit, and sufficient receiver sampling rate is available on receive, so antenna dispersion will be treated as an undesirable characteristic.

Separate transmit and receive orthogonally polarized antennas will be used to prevent coupling on transmittance and to gate out the ground reflectance if it is so desired. Another reason is that due to dispersion by the medium and dispersion and modulation by the target, the returning signal may have very different characteristics on receive that it had when transmitted. (The interface between air and soil does not produce the phase reversal (polarization reversal) which is present when the scattering is from a metallic surface, due to the relatively medium-to-low permittivity and conductivity of soil. However, some targets, e.g., pipes, have even lower permittivites than soil. T-R receive switches are not, in general, practical for antenna isolation due to the slowness of switching time). Bow-tie antennas have been used, but users report "ringing" or "ring down" which distorts the transmitted signal. The antennas must be broadband, if they are resonant antennas, and this family includes the nondispersive TEM horn antennas and the bow-tie antenna.

Antennas which have been used for ground penetration include: (i) element antennas, e.g., monopoles, cylindrical dipoles, biconical dipoles and the bowties; (ii) traveling wave antennas, e.g., helical antennas, the dielectric rod antenna and the long wire antenna; (iii) frequency-independent antennas, e.g., spiral: helical or planar; and (iv) aperture antennas, e.g., the horn antennas. The recently patented antenna of Wick and van Etten (1991) is a novel broadband quadridged horn and has been successfully used in ultrashort RF pulse (USPR) work.

There is also the small class of nonresonant antennas. Essentially, a nonresonant antenna is a discharging capacitor with a tapered match to the medium. The advantages of a nonresonant antenna is its small size which is possible because there is no steady state resonance required. Therefore the size-wavelength relationship no longer applies. The disadvantage of the nonresonant antenna is its efficiency. Efficiencies of only 12-15% have been reported.

The antenna system will be simulated for alteration of its transmit properties due to the close proximity of the ground surface (Brewitt-Taylor et al, 1981; Junkin & Anderson, 1988). This problem has been investigated at mm-wavelengths by Rutledge & Muha (1982). The "breakthrough" signal (from transmit to receive antenna) must be eliminated as much as possible, and this can be accomplished by use of the orthogonally polarized antennas aforementioned and the reduction of "ringing".

The footprint size of the antenna becomes ever more important as platforms are considered which are at a distance from the ground surface, e.g., as in air operation. The footprint size is reduced for larger distances and for highly attenuating surfaces. Although there is a reduction in beamwidth, there is, of course, no increase in gain. However, the major advantage is that there is an increase in horizontal resolution between targets at equivalent depths.

When a planar antenna is close to the ground surface, there is a preferential radiation into the higher permittivity with a concomitant beam narrowing and gain. The beam shape for a planar antenna at the interface between air and solid is changed from that for free space, with 98% radiated into the ground within a cone of angle 45^0 (Brewitt-Taylor et al, 1981; Rutledge, 1982; Smith, 1984). This reduction in beam width, or

Table 3.1. Ground Penetrating Radar: Antenna Design Characteristics	
	Characteristics's Features
1. Impulse Response	Extended impulse response undesirable.
2. Fractional Bandwidth	Limited instantaneous bandwidth undesirable in GPR antenna
3. Polarization States	Instantaneous polarization characteristics provide GPR signature for targets
4. Cross-Coupling to Receiver	Highly undesirable in GPR
5. Interaction of the Reactive Field with the Surface Medium	If known, can be compensated by processing
6. Modification of the Antenna Characteristics by a Target within the Near-Field of the Antenna	If known, can be sompensated by processing
7. Geometry (Planar versus NonPlanar)	Planar geometry provides easier radar return processing capability
8. Dielectric Loading	To isolate antenna's reactive and near-fields from the surface medium

focusing, occurs when the radiation is from afar and strikes the surface as plane waves. is also due to refraction for non-normal incidence. This type of refraction, together with an enhancement of the permittivity ratio for the backscattered signal, is the reason for Elachi et al (1984) observing a larger scattered signal from an object buried in sand, than one lying on the ground surface when illuminated from a satellite-borne system. Even with radiation from a remote antenna which is not so distant that the plane wave approximation foes not apply, the air-ground interface refraction works to reduce the angular beam width in the soil, resulting in greater subterranean target resolution.

Antenna design characteristics for subsurface radars are stated in Table 3.1.

Some of the characteristics of ground-penetrating radar antennas are shown in the following Table 3.2:

Table 3.2 Ground-Penetrating Radar: Antenna Types			
Generic Type	Examples of Type	Advantages for GPR	Disadvantages for GPR
Element Antennas	Monopoles, Cylindrical Dipoles, Biconical Dipoles, Bowties.	Small Physical Volume, Resistive Loading can extend performance.	Low Directivity, Linear Polarization, Limited Bandwidth, Low Gain, Low Radiation Efficiency.
Traveling Wave Antennas	V-Shaped Dipole operating in end-fire mode, TEM Horns.	Leaky Wave Modes supported resulting in continuous radiation. Linear Phase Characteristics; Short Impulse Response; 3 db beamwidths of $\pm 25^o$; Highly directive; Compact; Suitable for both bore-hole ad air-borne use.	

Frequency-Independent Antennas	Spirals: planar or helical, e.g., logarithmic, log-periodic, Archimedean.	Frequency Independence. Very large bandwidth achievable: 40:1. Can produce circularly polarized radiation.	Impulse response is extended (due to nonlinear phase response), resulting in chirp waveform. Therefore, phase correction needed. Planar spiral does not radiate unidirectionally (although the conical spiral does).
Aperture Antennas	Horn Antennas, Ridge Antennas.	Quadridged Horn can exploit polarization discrimination.	Large Size; Phase distortions caused by waveguide feeds; Phase distortions caused by the ridge.

Due to the linear phase characteristics, short impulse response, 3 db beamwidths of approximately $\pm 25^0$, as well as its proven use in ground-penetrating radar systems, the TEM horn antenna (Iizuka, 1967; Wohlers, 1970; Daniels, 1980; Pittman et al, 1982; Evans & Kong, 1983; Theodorou et al, 1981; Oswald, 1988) will be adopted in Phase III for air platform use. In the case of ground platform use, this antenna is both bulky and susceptible to the formation of standing surface return wave capture. Therefore for ground platform use, dipole antennas will be adopted.

3.2 Source Technologies

There are a number of high-power short pulse source technologies under development. For example, besides the well-known air-gap sources, and hydrogen pressurized switches, there are the light-activated semiconductor switches, in which the semiconductor can be silicon, GaAs, diamond and silicon carbide. All of these need to be laser-activated and all, except, perhaps for silicon-based, have major reliability, duty cycle, yield, filament creation or jitter problems. Furthermore, light-activated switches are certainly not needed in the Phase II proof-of-concept demonstrations. As the range of pulse durations of interest is in the 100's picosec.s to, at most 1-5 nanoseconds, and fast offset, as well as fast offset is important, avalanche transistors can provide the required peak powers of a few Watts.

In the case of the crafted waveshapes proposed for usi in the system development proposed Phase III, avalanche transistors will not provide sufficient peak power. The control of the gate in vacuum tubes is also not feasible due to the slow response time. Hydrogen pressurized switches are quite feasible, but cannot be programmed. Therefore, for programmable crafted waveshape source technologies, linear light-activated silicon switches are the proposed candidates.

3.3 Waveform Design

A variety of signal types have been used: AM, frequency-modulated continuous wave (FMCW), continuous wave (CW), stepped FM, as well as pulse. AM and CW techniques have many disadvantages, the main being that using low frequencies to penetrate lossy ground results in poor resolution. It is also much more difficult to process returning signals when the transmit signal is still operating. The stepped FM technique is a hybrid technique which requires lengthy processing and must also pay the penalty of drastic reduction in resolution in exchange for deeper penetration with lower frequencies.

The work proposed in Phase II will explore pulse methods but with variations in the pulse envelope in order to match the pulse to the medium and target. Airborne Environmental Surveys International has used frequency swept pulses (1-5 nsec. in duration). As the advantages of short pulses appear to lie in the rapidity of their onset and offset, rather than in the phasing of the frequencies under the signal envelope, such pulses fall within the purview of the present short pulse program.

Synthetic pulses have also been used (Robinson, 1974). However, both synthetic pulses and the FMCW technique suffer from size and cost limitations, as well as the possibility of induced interference. Pulse expansion/compression (chirp) techniques have also been used, but such techniques presuppose linearities in the medium - a presupposition which is untested and may not be true. If there are nonlinearities in the medium - and not merely of the intensity-dependent type - then there is the possibility of matching and exploiting the same, and such matching could not be accomplished by a strict adherence to FM techniques.

3.4 Receiver Technologies

The presence of strong reflections from the ground surface and possible leakage signals from the transmitting to the receiving antenna, as well as relatively weak returning signals necessitate powerful temporary automatic gain control to compress the dynamic range of the input signals. A genuine time domain receiver is required (cf. Barrett, 1995) which preserves the instantaneous frequencies and phase of the returned signals, and, at the same time, all ringing effects must be removed from the circuitry. The receiver paradigm must be a homodyne (rather than heterodyne) receiver, due to the nonlinearities imposed by a local oscillator, and the resulting loss of information and signal energy. Bulk acousto-optic devices are avilable which are fast enough (GigaHertz bandwidth) to preserve individual signal fine structure, but in tandem with CCD arrays are also able to respond to up to a µsec.-length data stream.(Generally, only 100-200 nsec.s of data stream is required). The receiver will acquire, amplify and autocorrelate the signal data stream, and then digitize and handover to the processor.

3.5 Processor Technologies

The signal processor functions in two modes: (1) the single probe detection mode; and (2) the multiple probing imaging mode. In both modes, the velocity of the signal through the layers will be estimated on semiempirical grounds and the hyperbolic migration will be detected and reduced or eliminated. Using GPS P-code positioning data, a three dimensional subsurface 3-D layer can be constructed with features of significance: voids, underground objects, water, etc., highlighted. When ground attenuation permits, synthetic aperture processing methods can be used.

The signal processing for ground penetrating radar, resulting in "user friendly" operation requiring minimum interpretation by experts, is not trivial and requires major software development (see below).

4. Data Collection and Processing Methods

The method of data collection is shown in Fig. 4.1. for one location along side-by-side tracks. The radar proposed for Phase III will have two modes of functioning. The first mode is a detection mode, without identification and characterization. The second mode is an imaging mode which requires mutiple probings at precisely defined locations. For the imaging mode, the intention is to build a three-dimensional display of ground media based on such data collections.

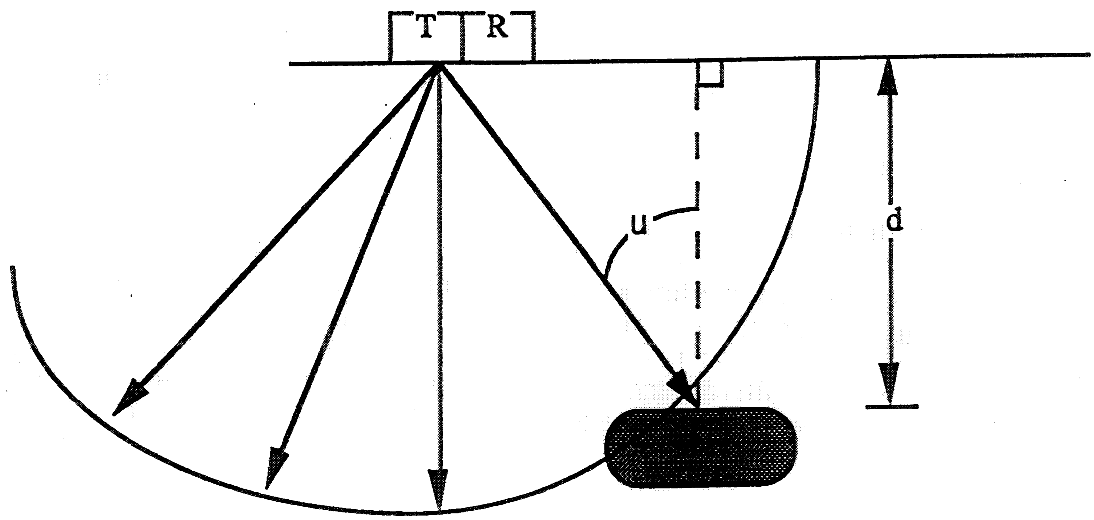

Fig. 4.1. Schematic showing data collection at a single location with recordings made at angle θ.

With an attentuation coefficient, α, and an inverse fourth power of decay the signal received is proportional to $\exp[\frac{-2\alpha d \sec\theta}{d^4 \sec^4\theta}]$. The resolution, Δx, is given by:

$$\Delta x = 4d\sqrt{\frac{\ln 2}{2+\alpha d}}$$

indicating that the sidelooking resolution *improves* as the attenuation increases.

Absorption occurs from both conduction and dielectric effects. Furthermore, one traditionally observes (King & Smith, 1981, p. 358) that in Maxwell's equations the dielectric constant, ε, and the conductivity, σ, always occur in the combination:

$$\sigma + i\omega\varepsilon = \sigma' + \omega\varepsilon'' + i\omega(\varepsilon' - \frac{\sigma''}{\omega}) = \sigma_e + i\omega\varepsilon_e,$$

where

$\varepsilon = \varepsilon' - i\varepsilon''$ is the complex permittivity,
$\mu = \mu' - i\mu''$ is the complex permeability,
$\sigma = \sigma' - i\sigma''$ is the complex conductivity,
$\varepsilon'_e = \varepsilon' - \sigma''/\omega$ is the real effective permittivity,
$\sigma'_e = \sigma' + \omega\varepsilon''$ is the real effective conductivity,
$\varepsilon''_e = \varepsilon'' + \sigma'/\omega$ is the imaginary effective permittivity,
$\sigma''_e = \sigma'' - \omega\varepsilon'$ is the imaginary effective conductivity.

For example, the propagation of electromagnetic waves is described by the wave equations:

$$\nabla^2 E = \gamma^2 E; \nabla^2 H = \gamma^2 H,$$

where

$$\gamma^2 = i\omega\mu(\sigma - i\omega\varepsilon)$$

or the square of the propagation factor.

When measurements are made on a conducting dielectric, the parameters measured are the apparent permittivity, ε_a, and the apparent conductivity, σ_a:

$$\varepsilon_a = \varepsilon - \frac{i\sigma}{\omega} = \varepsilon_e - \frac{i\sigma_e}{\omega} = \varepsilon_e' - i\varepsilon_e'' = \varepsilon_e(1 - ip_e),$$
$$\sigma_a = \sigma_e' + i\omega\varepsilon_e' = \sigma_e' - i\sigma_e'' = \sigma_e(1 + ip_e^{-1}),$$

where

$$p_e = \frac{\sigma_e'}{\omega\varepsilon_e'} = \frac{\sigma' + \omega\varepsilon''}{\omega\varepsilon' - \sigma''} = \frac{-\sigma_e'}{\sigma_e''} = \frac{\varepsilon_e''}{\varepsilon_e'}$$

is the effective loss tangent.

A relation exists between the measured apparent permittivity, ε_a, and the apparent conductivity, σ_a:

$$\sigma + i\omega\varepsilon = \sigma_e' + i\omega\varepsilon_e' = \sigma_a = i\omega\varepsilon_a.$$

Traditionally, the two measurements of interests in subsurface radar have been:

(1) wave attenuation as a function of frequency, and

(2) velocity of wave propagation as a function of frequency.

The present approach will calculate a third:

(3) wave dispersion as a function of frequency.

These three measurements are obtained from the apparent permittivity, ε_a, and its relation to the propagation constant, γ, the attenuation constant, α, and the phase constant, β:

$$\gamma = \alpha + i\beta = \omega\sqrt{\varepsilon_a\mu}.$$

If the permeability, μ, is taken to be ε_0, and with c the velocity of light in vacuo, the wave velocity, v, is:

$$v = c\left[\frac{\varepsilon_e'}{2\varepsilon_0}\left(\sqrt{1-p_e^2}+1\right)\right]^{-1/2};$$

the attenuation factor is:

$$\alpha = \frac{\omega}{c}\left[\frac{\varepsilon_e'}{2\varepsilon_0}\left(\sqrt{1+p_e^2}+1\right)\right]^{1/2};$$

or

$$129\omega\left[\varepsilon_e'\left(\sqrt{1+p_e^2}-1\right)\right]^{1/2} dB\, m^{-1},$$

with ω in GHz; and the phase shift constant is:

$$\beta = \frac{\omega}{c}\left[\frac{\varepsilon_e'}{2\varepsilon_0}\left(\sqrt{1-p_e^2}+1\right)\right]^{1/2};$$

The electromagnetic field E_0 originating at $z=0$, $t=0$ is described by $E(z,t)$ at a distance z and time t:

$$E(z,t) = E_0 \exp[-\alpha z] \exp[i(\omega t - \beta z)],$$

where $\exp[-\alpha z]$ is the attentuation term and $\exp[i(\omega t - \beta z)]$ is the propagation term. Therefore, the attenuation is $1/e$ at a distance $z = 1/\alpha$ or at the skin depth $\delta = 1/\alpha$. The phase shift, ϕ, is (Ulriksen, 1982):

$$\phi = \frac{1}{2}\tan^{-1}\left(\frac{\sigma_e}{\omega\varepsilon_e}\right).$$

The frequency-independent, steady-state conductivity, σ_s, is defined by:

$$\sigma = \sigma_s - (\sigma_s - \sigma') - i\sigma''$$

With those definitions stated, the following Tables provide a feel for the earth and water relaxation times involved. It is important to note that the properties of ("fresh") water are different from saline solutions and water mixed with earth.

Table 4.1 Static Permittivity, Relaxation Time, and Critical Wavelength of Water (From King and Smith, p. 409)

T(°C)	ε_{rs}	τ (sec x 10^{-12})	λ_c (cm) = $2\pi c\tau$.
0	88.2	17.8	3.34
10	84.2	12.7	2.39
20	80.4	9.5	1.80
30	76.7	7.4	1.39

Table 4.2 Static Permittivity, Relaxation Time, and Critical Wavelength of NaCl Solutions (Daniels et al, 1988)			
T(°C)	ε_{rs}	τ (sec x 10^{-12})	λ_c (cm) = $2\pi c\tau$.
0	73.5	17.6	3.31
15	69.2	10.7	2.01
25	66.7	8.3	1.56
35	63.5	6.5	1.23

The relaxation spectrum of water in soils is displaced to a lower frequency than in bulk water (Hoekstra & Delaney, 1979) and there appears to be two closely spaced relaxation times, rather than one, for water in soils.

If the low-frequency conductivity, σ', is adequate to describe the loss mechanism, and when ε'' and σ'' can be neglected, ε is equal to $\varepsilon' - \frac{i\sigma'}{\omega}$ and $p_e = \frac{\sigma'}{\varepsilon'\omega}$. Then at frequencies such that $p_e^2 < 1$, the loss becomes independent of frequency and is given by

$$\alpha = \varepsilon_r' \frac{\sigma'}{2\varepsilon' c}.$$

Table 4.3 Relaxation Times and Losses for Heterogeneous Mixtures Containing Water and Frequency Range (From De Loor, 1983)	
	ω
ice, relaxation	32 Hz - 31.6 KHz
water relaxation	1.58 GHz - 200 GHz
Maxwell-Wagner losses	7.9 Hz - 1 GHz
conductivity	0 Hz - 1.26 GHz
crystal water relaxation	20 Hz - 20 KHz
bound forms of water relaxation	1 GHz - 1.58 GHz
surface conductivity	1.6 KHz - 2 GHz
charged double layers	0 Hz - 40 KHz

For moist soil with $\varepsilon_r' = 10$ and $\sigma' = 10^{-2}\ S\ m^{-1}$, the attenuation rises with frequency up to 20 MHz and then flattens out at about 5 dB m^{-1}.

As stated initially, there is considerable overlap with seismic methods (Jurkevics & Wiggins, 1984). The real-time response recorded is (Daniels et al, 1988):

$$\omega_r(t) = \omega_s * \omega_a * \omega_b * \omega_g * \omega_u * \omega_g * \omega_a + n,$$

where

ω_s is the signal applied to the antenna,

ω_a is the antenna response,
ω_b is a matching function antenna-to-ground,
ω_g is the response of the ground,
ω_u is the response of the underground target,
n is noise.

The raw data must then be treated with the following procedures.

4.1 Removal of Noise

There are a number of approaches, e.g.:

4.1.1 Average Noise Removal

$$\omega_{bi} = \omega_i(n) - a_i(n), i = j.....j + N_a - 1$$

$$\text{where } a_i(n) = \frac{1}{N_a} \sum_{k=j}^{j+N_a-1} \omega_k(n),$$

$\omega_{bi}(n)$=value of record n after background removal,
$\omega_i(n)$=registered value of record n,
$a_i(n)$=average noise level,
N_a=number of records in the computed average,
j=record number at which the computation of average is started.

4.1.2 Decaying recursive filter system approach:

$$A(n) = A(n-1) + \frac{D - A(n-1)}{\tau},$$

$A(n)$ = new average,
$A(n-1)$ = stored average,
D = computed average of N scans,
τ = filter time constant.

4.1.3 Whitening:

$$\omega_{wi}(n) = F^{-1}(FW_i(m)), i = 1...N,$$

$$FW_i(m) = F_i(m)A_i(m),$$

$$A_i(m) = \left[\frac{a+\varepsilon}{|F_i(m)| + \varepsilon}\right]^c,$$

where

$F_i(m)$ = the Fourier spectrum of the return,
$A_i(m)$ = the whitening factor,
$|F_i(m)|$ = absolute value of $F_i(m)$,
a = maximum value of $|F_i(m)|$ or of the average of $|F_i(m)|$ over all the N records,
ε, c = empirical constants.

4.1.4 Filtering techniques, e.g., Wiener filtering, Kalman filtering, wavelet filtering (see below).

4.2 Target Polarization Properties:

Polarization sensitivity of the target will be exploited by using a pair of orthogonally polarized transmit and receive antennas.

4.3 Kirchhoff Methods

If $V(x,y,0,t)$ is the measured data and x,y are surface coordinates, z is depth and t is time, the integrated wavefield at some point (x_1,y_1,z_1,t) is obtained as (Safar, 1985; Schneider, 1978; Osumi & Ueno, 1988; Yeung & Evans, 1988):

$$V(x_1,y_1,z_1,t=0)=\iint\left\{\frac{\cos\theta}{2\pi c}\right\}\left\{\frac{\partial}{\partial t}+\frac{c}{r}\right\}V(xyz,t=0)dxdy,$$

where the straight line distance between $(x,y,z=0)$ and $(x_1y_1z_1)$ is r; θ is the angle between this line and the z axis, t is the two-way transit time and c is the half-velocity $v/2$. There is a close similarity to synthetic aperture methods except that in conventional synthetic aperture applications $\cos[\theta]$ is constant and r varies linearly with x and y for a given value of θ, rather than hyperbolically as in the case of subsurface radar.

4.4 Velocity & Depth Determination:

One method for determining velocity and depth is as follows (Fig. 4.2): As an antenna moves across a target, the distance, s, to the target is a hyperbolic function of x and z:

$$s=\sqrt{(x^2+z^2},$$

the distance is then:

$$z=\frac{|x_i|}{\sqrt{\left(\frac{t_i}{t_o}\right)^2-1}},$$

and the average velocity, v_a, is:

$$v_a = \frac{z}{t_0}.$$

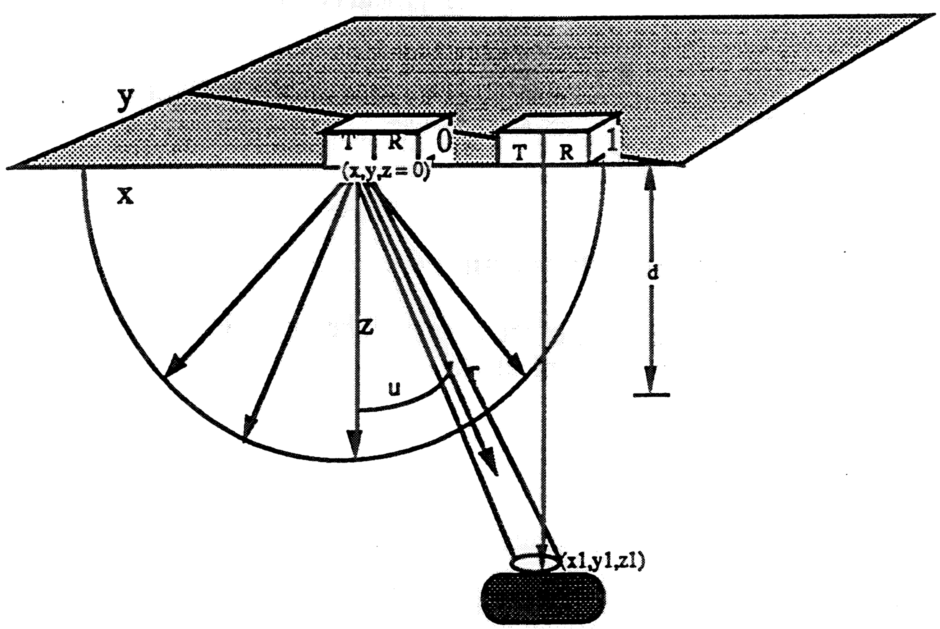

Fig. 4.2. Configuration for data collection and a reference for the three-dimensional processing scheme. Two positions of the transmit and receive antennas shown. The half-velocity, c = v/2, must be estimated.

4.5 The Hyperbolic Stacking Correction for Hyperbolic Migration

Hyperbolic stacking is the process of summing all the energy of the hyperbolic tails in vertex points (Fig. 4.3). An algorithm to do this is (Ulriksen, 1982):

$$f_i(t) = \sum_k a_{ik} g(t - T_{ik}),$$

where
$g(t)$=the transmitted signal,
a_{ik}=complex coefficient representing transmission loss and scattering strength of the k'th unit scattering volume.
Then:

$$h_i(t) = \frac{\sum_{m=-M}^{M} f_{i+m}(t + T_m)}{\sum_{m=-M}^{M} f_{i+m}(t)},$$

where

$$T_m = \frac{1}{c}\left[(x_i - x_{i+m})^2 + (ct)^2\right]^{1/2}.$$

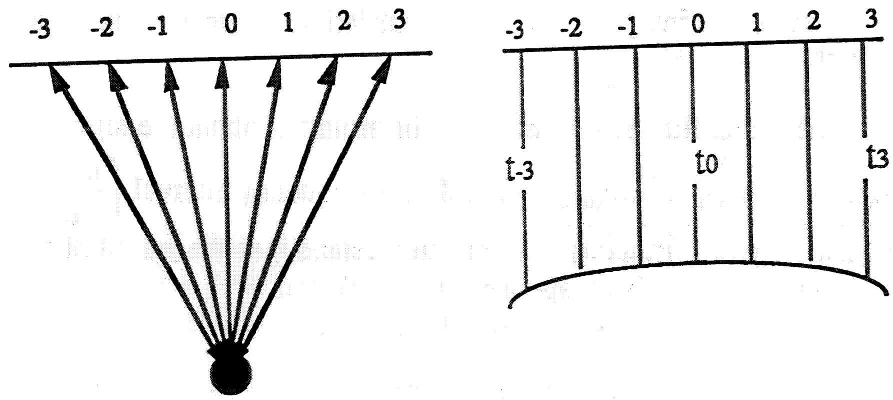

Fig. 4.3. Hyperbolic migration which disperses the vertex point and hyperbolic stacking which recovers the vertex point.

4.6 Wavelet Analysis & Clutter Rejection

Processing for GPR involves the preservation of instantaneous signal events. The mathematical technique best suited to instantaneous event analysis is wavelet analysis. Wavelet analysis is in terms of local events and regards signal decomposition as a detection-estimation problem. Therefore cross-correlation operation amounts to a matched filter *in two-dimensions*, which can be used to filter out noise, e.g., ground clutter. As wavelet decomposition amounts to the two-dimensional filtering of the signal and the representation of the result of that filtering, the ambiguity function can be interpreted as a picture of the results obtained from using various kinds of two dimensional filters on the signal. Wavelet analysis will be used in treatment of returning signal data streams in order to remove noise and clutter. Let

$$s(t) = A_s(t)\exp[i\phi_s(t)] \qquad (1)$$

represent the signal, and

$$g(t) = A_g(t)\exp[i\phi_g(t)] \qquad (2)$$

represent the wavelet. The wavelet transform $S(b,a)$ of a square integrable signal $s(t)$ is obtained by its scalar product with respect to a *dilated* (by $1/a$) and *translated* (in b) version of a basic wavelet $g(t)$. The *wavelet transform* is defined as:

$$S(b,a) = \frac{1}{a}\int A_s(t)A_g\left(\frac{t-b}{a}\right)\exp(iL(t))dt, \qquad (3)$$

where

$$L(b,a,t) = \phi_s(t) - \phi_g\left(\frac{t-b}{a}\right) \qquad (4)$$

is the phase of the integrand, b is the translation parameter and a is the dilation (scale) parameter.

The transform $S(b,a)$ provides information about the signal *simultaneously* on a time-interval $(at_{\min} + \tau, at_{\max} + \tau)$ and on a frequency interval $\left(\frac{\omega_{\min}}{a}, \frac{\omega_{\max}}{a}\right)$. What is the wavelet transform *physically?* We can understand it as the output of a bank of linear band-pass filters with impulse response $g*(-t/a)$ and with effective width of those filters $G(a\omega)$ (where $g*$ indicates the complex conjugate and G indicates the Fourier transform of g). But this means that the analysis or filtering is *with constant* $\frac{\Delta\omega}{\omega}$ *or constant* $\frac{1}{Q}$. Therefore the continuous wavelet transform permits an analysis of the signal with an arbitrary but constant value of $\Delta\omega / \omega$ (arbitrary $1/Q$). Suppose we look at one *voice* of a transform, that is, a restriction of the transform to a fixed frequency, then a major difference between the Fourier transform and wavelet analysis is that in the wavelet case, the impulse response of the equivalent filter (the wavelet) is contracting as the frequency analysis increases (i.e., the scale decreases) *while it is of fixed length in the Fourier case. That is why a wavelet transform is called an analysis with a constant* $\frac{\Delta\omega}{\omega}$ *and the Fourier transform a constant* $\Delta\omega$ *analysis.*

The proof-of-concept demonstration in Phase II is designed to show that an optimum pulse waveform defined precisely with respect to both time and frequency characteristics will provide (a) optimum medium penetration and reflectance from targets; and (b) reduced clutter. Consider, now, the signal which is the differential of a Gaussian, which is similar to a ground penetrating signal emitted and, perhaps, received (Fig. 4.4):

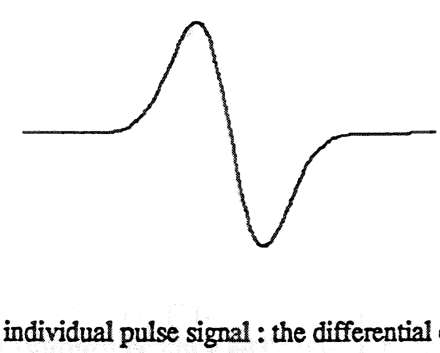

Fig. 4.4. An individual pulse signal : the differential of a Gaussian.

Using the Mallat wavelet, g, and using Eq. (3) we can plot the modulus of the wavelet transform, $|S(b,a)|^2$, over the half (a,b) plane (Fig. 4.5.). This plot provides information concerning the density of energy in the pulse, over time (the x-axis), over frequency (the

y-axis). Notice that the plot is in reciprocal frequency, so the high frequencies are at the bottom of the plot and the low frequencies at the top.

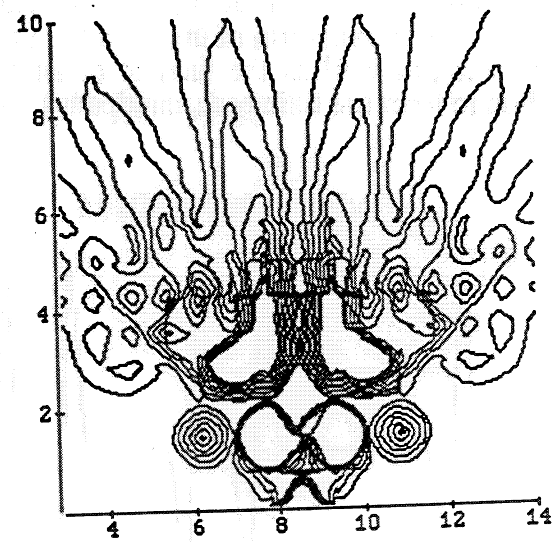

Fig. 4.5. The modulus, $|S(b,a)|^2$ or density of energy for the single pulse of Fig. 4.4. Contour lines of constant energy amount are shown. The abscissa is reciprocal frequency. The ordinate is time.

We can also look at the phase of this signal using Eq. (4). Fig. 4.6. shows lines of constant phase (y-axis) over the time duration of the pulse (x-axis). Clearly, within the single pulse duration there is not an instantaneous bandwidth. The intention is to map the changes in signal phase existing in the returned signal. By detailed undertstanding of the emitted pulse in the time and frequency domains, it is possible to match the pulse to a class of targets - mines - for maximum target return and minimum clutter return.

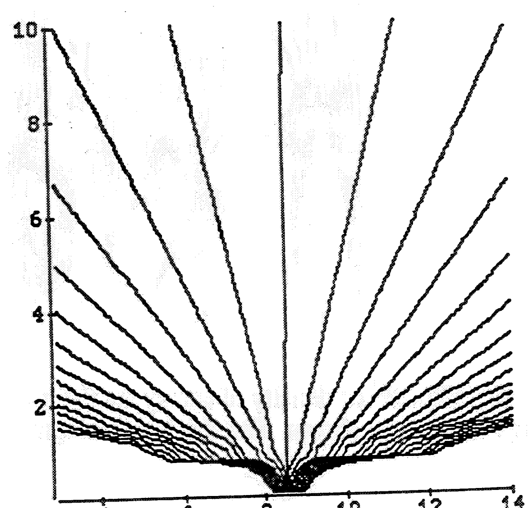

Fig. 4.6. The phase (lines of constant phase) for a single pulse. Lines of constant phase are shown. Abscissa is phase, ordinate is time.

Another method for reducing clutter and also multipath is to provide a pulse train with known interpulse interval coding. The return from a target should preserve that coding. Multipath will not. Therefore pulse train coded signals will be considered for providing increased signal-to-noise by multipath rejection. Analyzing a pulse train of such pulses, e.g., 10001100111, as shown in Fig. 4.7. and using the methods described above, the modulus of the wavelet transform of the pulse train can be calculated, as shown in the half plane in Fig. 4.8., as well as the lines of constant phase in Fig. 4.9. By using a correlator locked-on to the pulse train code, multipath signals are gated out.

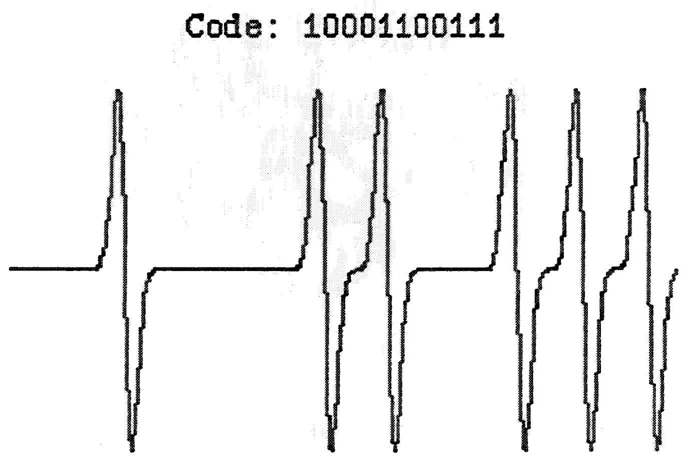

Fig. 4.7. The pulse train 10001100111.

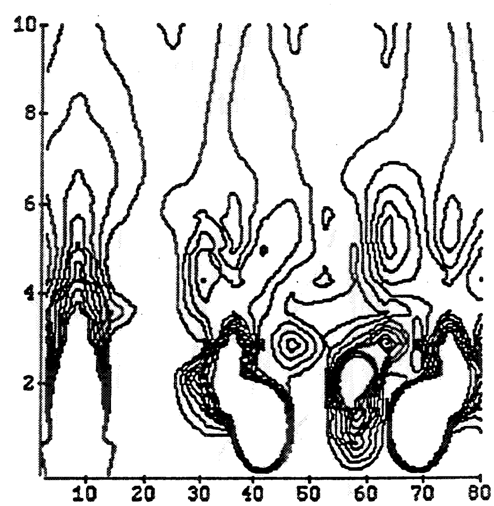

Fig. 4.8. The modulus, $|S(b,a)|^2$ or density of energy for the pulse train 10001100111. Contour lines of constant energy amount are shown. The abscissa is reciprocal frequency. The ordinate is time.

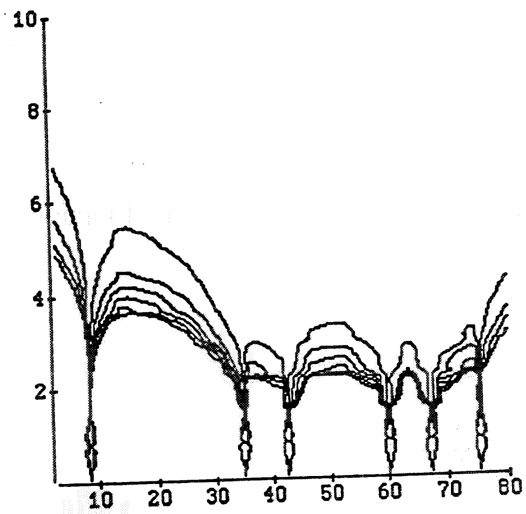

Fig. 4.9. The phase (lines of constant phase) for the signal train 1000110111. Lines of constant phase are shown. Abscissa is phase, ordinate is time.

A more complicated waveshape is show in Fig. 4.10., which is the addition of two constant frequency sinusoids. The modulus of the wavelet transform of this waveshape is shown in Fig. 4.11.

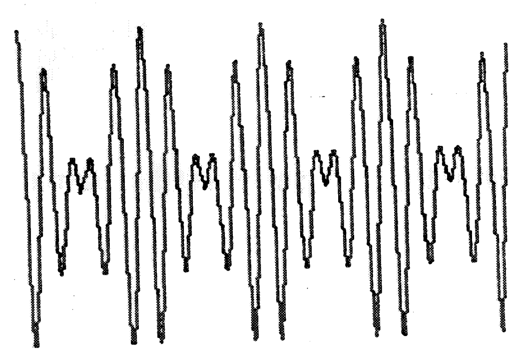

Fig. 4.10. Cos[ax] + Cos[bx].

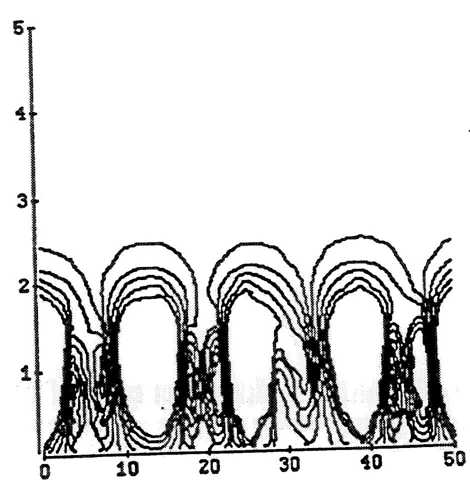

Fig. 4.11. Modulus of the wavelet transform of Cos[ax]+Cos[bx].

Fig. 4.12. shows the full plane ambiguity function plot of five coherent pulses.

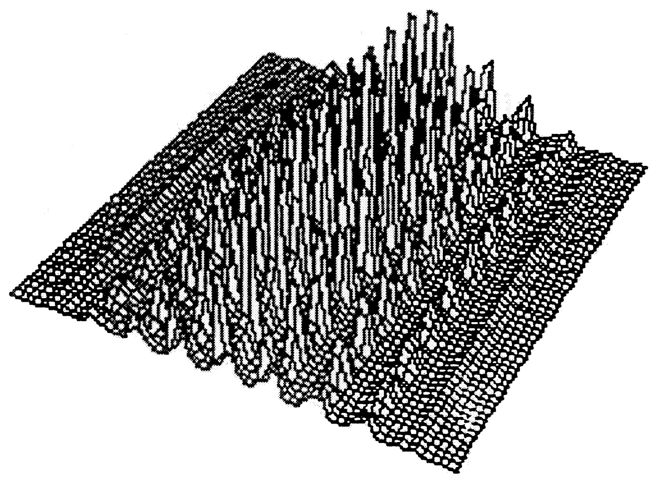

Fig. 4.12. This is the full ambiguity diagram plot of five coherent pulses. The function represented is:

$$|X(\tau, \nu)| =$$

$$\frac{1}{N} \sum_{p=-(N-1)}^{N-1} \left\{ \left| (1 - \frac{|p|}{N}) \exp\left[-N(\tau - p)^2\right] \right| \left| \sin\left[\frac{\pi}{N}\left(1 - \frac{|\tau - p|}{N} \nu\right)\right] \right| \left| \left[\frac{\sin[\pi t_p \nu]}{\pi t_p \nu}\right] \right| \left| \frac{\sin\left[\pi \nu (N - |p|) T_R\right]}{\sin[\pi \nu T_R} \right| \right\}$$

$$t_p < \frac{T_R}{2}$$

Wavelet filtering can be used to characterise the emitted signal, the returned signal, as well as unwanted clutter. It is then possible to design an optimum signal for target interaction and characterisation with minimum interaction with clutter or multipath hindrance.

4.7 Radar Range

The capacity of a radar to detect an echo of power P_r, if the transmitted power is P_t, is the performance figure:

$$S=\frac{P_t}{P_r} \text{ or}$$

$$S=10\log\left[\frac{P_t}{P_r}\right].$$

P_r is calculated in accordance with (i) the dielectrical considerations outlined above with respect to the passage to and from the target, and with (ii) geometrical optical arguments for reflectance from the target if the wavelength is short with respect the the illuminated target.

5. Waveshape Crafting: Simulation of Test Experiments

In Phase II a proof-of-concept demonstration will be undertaken addressing the effectiveness of increased media penetration, target detection, as well as clutter rejection, of the waveshape crafting approach to signal design patented by Barrett[1]. In Phase III, a system based on this approach will be constructed. The necessity of using this approach is due to the dispersive and absorptive nature of the ground medium and the differences in the underground targets sought.

For example, the dispersive nature of the medium is represented in Fig. 5.1. Conventional wisdom concludes that the ground medium is a low-pass filter. However, the fact that a high frequency monocycle is received back from a target as a lower frequency, is due, in the instance represented, to the disperive nature of the medium. Using an initial lower frequency monocycle results in even greater dispersion.

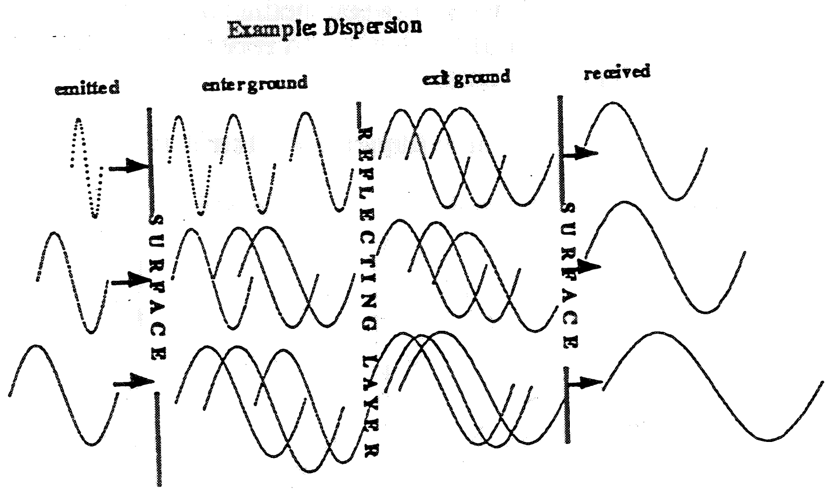

Fig. 5.1. An example of a medium which is dispersive. Three pulses of increasing duration are shown. The enter and exit pathways are shown separately. The reflecting layer is shown as not distorting the reflected signals - which would not be true in practice.

The medium is also absorptive (Fig. 5.2). Conventional wisdom also states that the ground medium is more absorptive for higher frequencies than low. However, if (1) the monocycle is shorter than the relaxation time of the medium, and (2) wave packet

[1]Barrett, T.W., An Optimum Active Signaling System Design Technique in Time-Frequency Space, U.S. Patent Office, 1995.

coherency is retained, then high freqency, i.e., shorter duration, monocycles can be used (cf. Barrett, 1991, 1995a). The desirability of using short duration monocycles is due to the better resolution capabilities of the shorter duration signals.

Example: Absorption

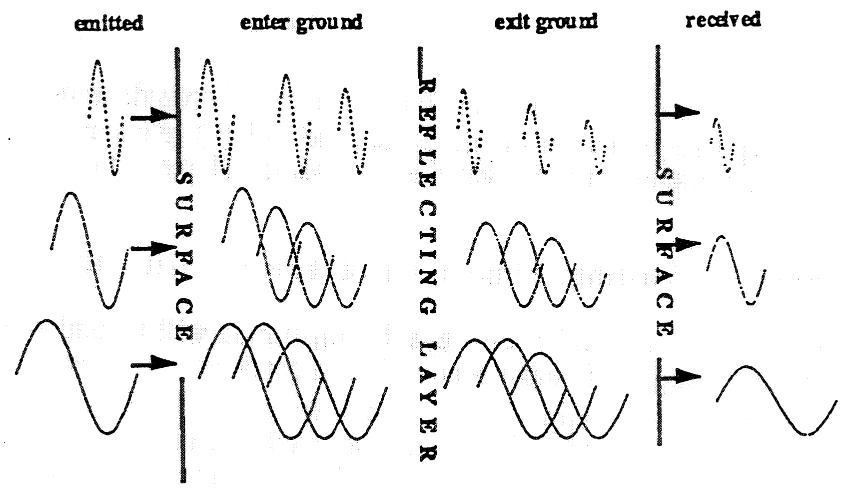

Fig. 5.2. An example of a medium which is absorptive. Three pulses of increasing duration are shown. The enter and exit pathways are shown separately. The reflecting layer is shown as not distorting the reflected signals - which would not be true in practice.

The medium can be both dispersive and absorptive (Fig. 5.3.). The reflecting target can also distort, or change, the signal characteristics (not shown in Fig. 5.3.). Therefore, an optimum pulse shape preserving medium penetration characteristics and also maximum interaction with the target will vary between media and between targets. The present use of a single signal for penetration of all media and reflection from all targets, is nonoptimum for most of those media and targets.

Example: Dispersion & Absorption

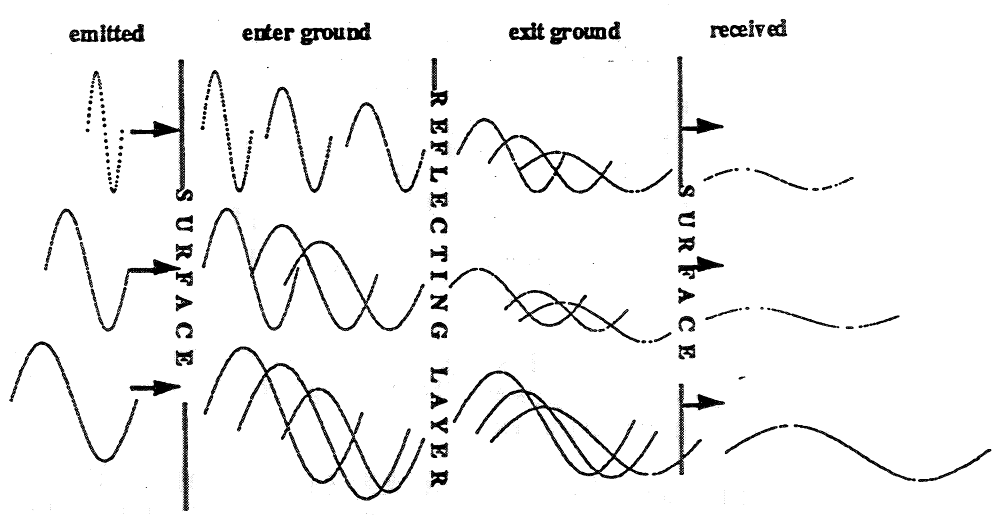

Fig. 5.3. An example of a medium which is both dispersive and absorptive. Three pulses of increasing duration are shown. The enter and exit pathways are shown separately. The reflecting layer is shown as not distorting the reflected signals - which would not be true in practice.

For this reason, the patented approach to optimum signal design will be attempted in Phase II. The approach requires obtaining the impulse response of the medium→target→medium. That response is then time reversed, i.e., the complex conjugate is obtained, and then used as the emitted signal. Such a signal is optimum for receiving a maximum returned echo from the target (Fig. 5.4.).

Example: Crafted Waves for Optimum Propagation

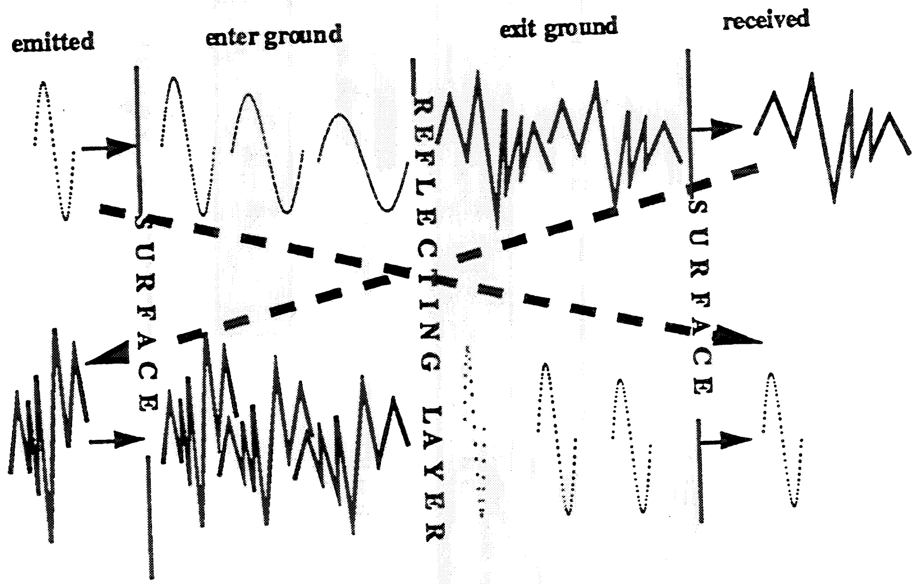

Fig. 5.4. The paradigm for crafted wave addressing of selected targets. Firstly, a short pules is used to obtain the impulse response of both the target and the absorptive and dispersive medium for both entering and exit paths (upper figure). That impulse response is then time reversed, amplified and then transmitted, resulting in a high signal-to-noise return from a selected target or class of targets (lower figure).

In order to enhance the signal-to-noise from specific targets, and in the case of multiple targets at different depths, signals will be optimized for those specific targets and depths (Fig. 5.4.). If targets and the media in which they are embedded differ greatly, then one signal cannot be optimum for both. Therefore, the signal-to-noise for both targets can be enhanced by using separately matched pulses for each.

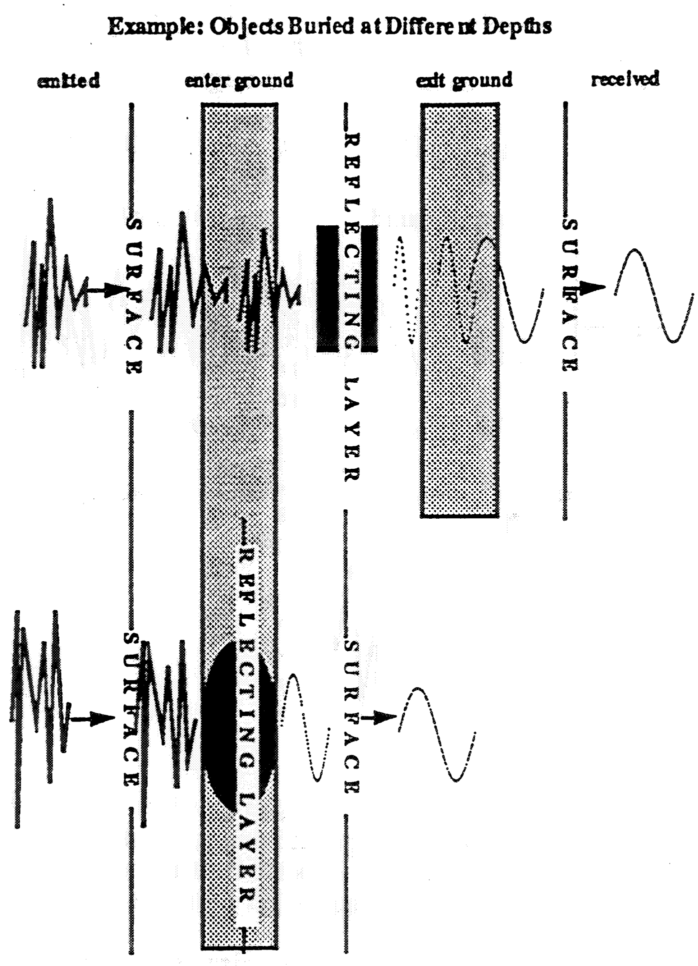

Fig. 5.5. Two different crafted pulses are shown matched to two different kinds of target, which are at different depths in the ground. Both pulses are the complex conjugate of the impulse response of the target and the ground medium. Each path selectively interacts with the target to which it is matched, providing decreased clutter and increased signal-to-noise.

As an exercise and to illustrate the methods proposed for the proof-of-concept demonstration in Phase II, the following simulations were performed[2]. In Fig. 5.6. is shown a conventional ground-penetrating radar pulse, used as a test pulse. The "impulse response" from subterranean layers and a reflecting layer or target is shown (target #1).

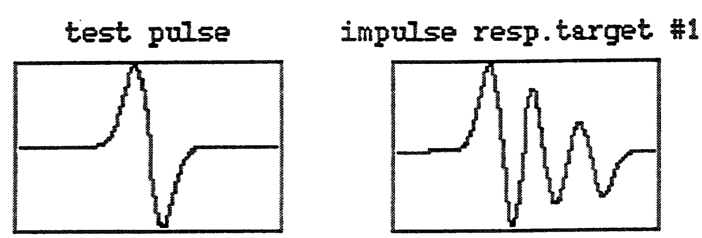

Fig. 5.6. A test pulse is shown on the left and the simulated impulse response from a subterranean layers and reflecting layer (target #1) on the right.

[2]Based on: Barrett, T.W., An Optimum Active Signaling System Design Technique in Time-Frequency Space, U.S. Patent Office, 1995.

The same test pulse is used to obtain the "impulse response" from another, and different, set of subterranean layers and reflecting layer or target (target #2) - Fig. 5.7.

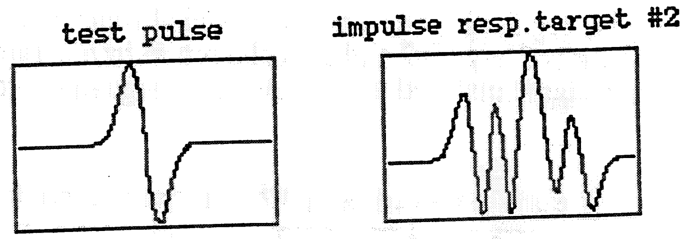

Fig. 5.7. The test pulse of Fig. 5.6. is shown on the left and the simulated impulse response from another, different, set of subterranean layers and reflecting layer (target #1) on the right.

Using the returned signal from the test pulse, a wave packet is crafted, or formed, which is the time-reversed of that returned from the test pulse, i.e., it is the complex conjugate of the "impulse response" of target #1 (Fig. 5.8., left). Using this complex conjugate signal as a transmitted signal, the echo or return signal from target #1 is calculated (Fig. 5.8., right). This signal return to the crafted pulse has a greater signal-to-noise level, and has less harmonic components than the return signal in response to the uncrafted test pulse.

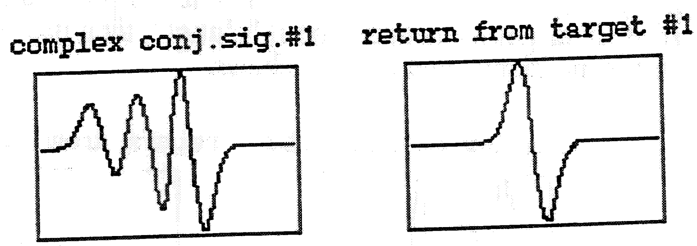

Fig. 5.8. The complex conjugate of the "impulse response" of target #1 (left) used as a probe signal and the echo response from target #1.

Fig. 5.8. is to be contrasted with Fig. 5.9., which shows the echo response of target #2 to the probe signal crafted as the complex conjugate to the "impulse response" of target #1. There is a greatly reduced signal-to-noise ratio. Thus, a signal crafted or matched to one set of objects, or layers, can reduce clutter from other sets of objects, or layers - where clutter is defined as that which is arbitrarily, and perhaps temporarily, designated as a target of no interest. In these simulations, the mathematical descriptions of the impulse response of target #1 and target #2 are relatively orthogonal. This accounts for the great

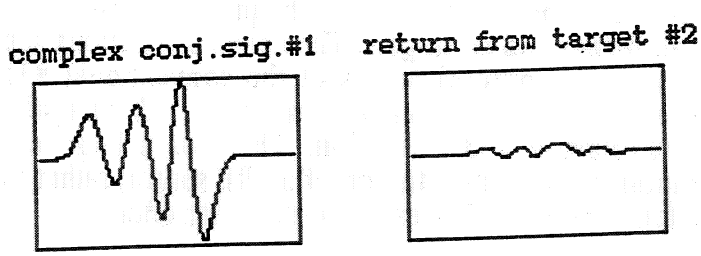

Fig. 5.9. The complex conjugate of the "impulse response" of target #1 (left) is used as a probe pulse and the return signal from target #2 is shown (right).

difference in response to the same probing signal of target #1 versus target #2. In experimental tests, it is expected that the transfer function and reflecting characteristics of some targets, or layers of media will to varying degrees from that of others.

Similarly, Fig.5.10. (left) shows the signal which is the complex conjugate of the "impulse response" of target #2 and the echo return from target #2 (right). As in Fig. 5.8., the return from a signal matched to its target has a large signal-to-noise ratio and an absence of dispersion.

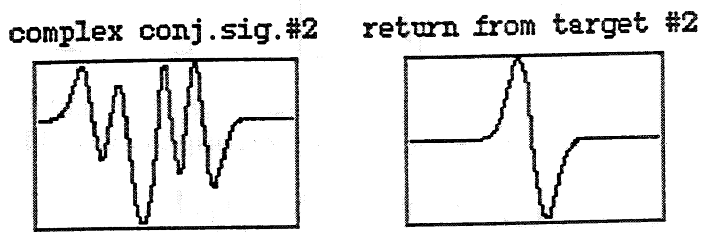

Fig. 5.10. The probe signal which is complex conjugate to the "impulse reponse" of target #2 (left) and the response of target #2 to this probe signal (right).

Fig. 5.11. shows the echo response from target #1 to the probe signal crafted as the complex conjugate of the "impulse response" of target #2. As in Fig. 5.9., the echo respose from a target in response to an unmatched probe signal, is greatly reduced in signal-to-noise. If target #1 is considered "clutter", then use of such a signal maximizes designated target interaction and reduces clutter.

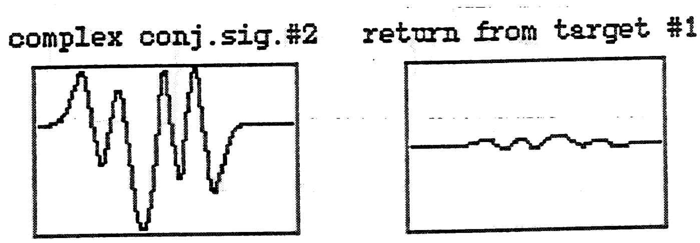

Fig. 5.11. The probe signal which is the complex conjugate of the "impulse response" of target #2 (left) elicits an echo response from target #1 which is greatly reduced in signal-to-noise.

These simulations are representative of both "targets" and the media in which those "targets" are embedded. Signals can be crafted to be matched to both media (for maximum transmissivity) and also to "targets" or geological discontinuities and strata (for maximum reflectivity and resolution of detail). The present conventional wisdom is to use the same pulse for all media and all targets. The above simulations suggest the inefficiency, and in some cases, the inappropriateness of the conventional wisdom. Using the techniques described here, RF wave packets can be crafted for optimum media penetration and optimum resolution and reflection. Thus, to a large degree, the proof-of-concept demonstration is the demonstration of an RF sensor, rather than a conventional radar, for which the term "radar" indicates ranging and detection.

A3.7 Phase II and Phase III USP Radar Data System Schematics

In Phase II, a very simple modification to the existing radar either from System & Software (S&S) or from AES will be made. The system modification to the S&S pulseEKKO 1000 are shown in the following Fig. 7.1.

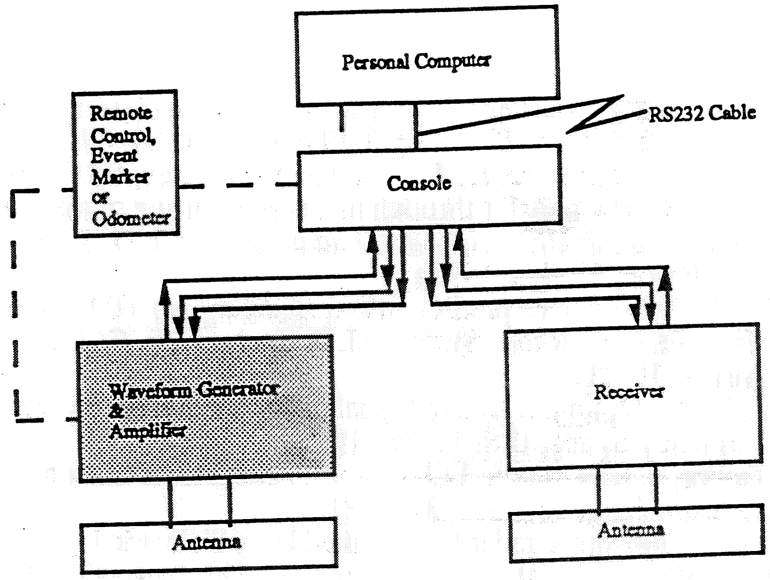

Fig. 7.1. Sensors & Software Inc.'s pulseEKKO 1000 system block diagram modified to include waveform generator and amplifier.

The system block diagram shows that the pulseEKKO transmitter has been replaced by a waveform generator and amplifier, e.g., the Hewlett-Packard 71604B. This is a straightforward replacement and, together with the choice of antenna, permits the required data.

In Phase III, a more refined system will be used as shown below:

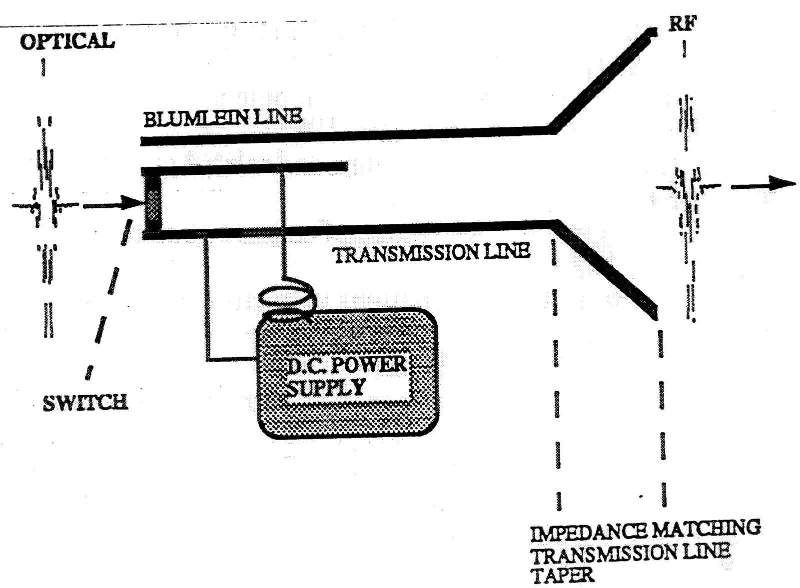

Fig. 7.3. Blumlein line representation of light-activated switch-driven antenna. The pulse crafting is placed on the incident light and a linear semiconductor switch activated.

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Volume II
Appendix III-2

Neutron Imaging For Surface and Subsurface Mapping

1. Survey Plan

a. Background

ii. Sources of Current Data

(3) Other data sources

To support and prepare the neutron imaging investigation, two principal types of information were necessary: the top soil and ground water chemical compositions and a list of the main chemicals of concern. The documents reviewed to extract this information were:

(D1) Parts of the Marshall Space Flight Center Environmental Resource Document.
(D2) Parts of the 1993 RCRA Facility investigation (RFI) work plan.
(D3) Parts of the 1991 RCRA Facility investigation (RFI) work plan.
(D4) Parts of the Natural Resources Management Plan for Redstone Arsenal.

(3) a. Chemicals of concern

The efficiency of the techniques to be used for the detection and mapping of chemicals depends on the particular chemicals to be investigated. It is therefore important to identify the chemicals of concern for the particular site to be investigated. Detailed environmental records and the general history of the site have provided us with significant leads as to which chemicals one should expect to find. Historically, the Redstone Arsenal was the site of manufacturing and loading plants for chemical ammunitions and was the main center for rocket research. Operations taking place on the present day location of MSFC included the manufacture of mustard gas (dichlorodiethyl sulphide: (ClCH2CH2)2S) and white phosphorous incendiary material.

The MSFC site itself has been and still is a principal propulsion development center (D2) of the National Aeronautics and Space Center. The center is managing the space shuttles main engines, solid rocket boosters, and external tank. The wastes generated and managed by NASA are (D2) organic solvents, rocket fuels, metal finishing and plating wastes, oils, acids, bases, paints, photographic waste, and construction debris, etc. A list of the hazardous wastes relevant for MSFC site as well as a list of all the hazardous substances used a MSFC are also included in the Environmental Resources Document While, for the technique suggested, a large number of these substance could be detected in the soil provided that their concentration is significan enough, such a comprehensive survey would be beyond the scope of thi proof of concept test. A more compact list containing the main chemical of concern potentially found on the MSFC site was therefore drawn. The first selected chemicals were listed in the RCRA RFI work plan as "preliminary contaminants of potential concern". This list contains the following chemicals: TCE - Chloroform - Perchloroethylene - Benzene - Xylene - Beryllium. Another series of chemicals added to this list were the substances with health concern that are emitted during rocket testing HCl, HF, Aluminum Oxides, Boron Oxides, SO_2, Aluminum, and CO The MSFC resource document also listed a series of discharge limitations and monitoring requirements for the site. The following elements were specifically listed: Cadmium - Chromium - Copper - Lead - Nickel - Silver - Zinc - Cyanide. These elements being potentially found on the site were also included into the list of chemicals to be sampled for.

Another source of chemicals are the ground and surface waters. Significant amounts of DDT (dichlorodiphenyltrichloroethane) coming from the drainage of a former DDT manufacturing area were detected prior to remedial action taken in 1986. Even though DDT was not detected since then in the majority of groundwater samples (less than 0.5 ppb) except for the wells directly around the former manufacturing area, this chemical was retained as one of the chemicals of concerns.

Besides the chemicals of general concern for the MSFC site, the beta site has also its own history and characteristics. Among the relevant history of the site (D1), 2 areas were among the one selected as candidate Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites. These two sites are: site 2 "Cyanide pit", and site 3 "Abandoned Drum Disposal Area". The cyanide pit corresponds to the location of a former metal plating shop. Cyanides are inorganic salt containing the cyanide ion CN^-. Due to their extremely poisonous nature, cyanides are definitely chemicals of concern. An outfall point is located near the sites, and the wastewater is frequently monitored. As for the abandoned drums, no specific information was found as to their original content and they will therefore not be specifically retained as far as the list of chemicals of concern. The complete list of identified chemicals is listed in a later section.

(3) b. Top soil and ground water composition.

To accurately assess the potential of the application of the techniques, one needs to model the soil composition as well as the surface and ground water compositions for surveys conducted in wells. This data will be used in particular to compute the average mean free paths of photons and neutrons in the top soil. These parameters are important to assess the sampled volume and survey geometry for the neutron imaging technique.

Most of the MSFC site is covered by soils of the Decatur-Cumberland-Abernathy Association. The soil is composed primarily of insoluble residue produced by chemical weathering of the underlying Tuscumbia limestone. This type of soil has also a high moisture holding capacity. This latest characteristic coupled with the frequent precipitation can lead to significant water fractions for the upper soil. The water content of the upper soil is an important parameter for the neutron imaging technique and the neutrons mean free path in particular. More specifically, the beta site topsoil can be characterized as an "improved ground". The general characteristics of the improved grounds of the Redstone Arsenal (D3) are:

- Sand 8 %
- Silt 35 %
- Clay 55 %
- Organic Matter 2 %

Silt and sand being mostly composed of quartz, and the clay material probably also containing some quartz, the top soils will be modeled as containing 50 % SiO_2. Besides its quartz content, the clay will be modeled as being Kaolite based and containing a significant amount of limestone. Iron oxide was also added into the soil mixture to account for frequent iron nodules. The overall modeling of the soil is the following: 50% SiO_2 - 35% $Al_4Si_4O_{10}(OH)_8$ - 14% $CaCO_3$ - 1% FeO. Being used to simulate photon and neutron ranges in the formation, this model does not yet require to be very precise and will be further refined during the second phase of the overall project. As for the surface water, the principal mineral constituents for Madison county (D1) are calcium, magnesium and bicarbonate, they will also be included in the next phase of the project when the analysis requires it.

b. Site Conditions and Environmental Variables

iv. Chemicals

(1) Known distribution/fate

From the available data (see paragraph a.ii(3)), a series of chemicals of concern were identified. These chemicals included all the chemicals specifically listed in the available reports as having been detected in excessive quantities on the MSFC site. The list also contained chemicals specifically used on the beta site as well as some chemicals used across the MSFC site in the open environment. The table presented below lists these chemicals. This list is not complete and is based on partial documentation and should therefore not be used for other purpose than this project. However, for this project, this list provides a wide cross section of chemical types which will allow to assess the capability of tl technique suggested for the detection of chemicals and mapping chemical plumes in the near ground surface.

Types of Chemical	Chemicals of Concern
Metals	Aluminum & Aluminum oxides - Beryllium Cadmium - Chromium - Copper - Lead - Nickel Silver - Zinc.
Organic Solvents	TCE ($CHClCCl_2$) - Chloroform ($CHCl_3$) Perchloroethylene ($(CCl_2)_2$) - Benzo(a)pyrei ($C_{20}H_{12}$) - Benzene (C_6H_6) - Xylei ($(CH_3)_2C_6H_4$).
Other chemicals	Boron oxides - Cyanide (CN^-) - DD ($(ClC_6H_4)_2CH(CCl_3)$) - HCl - HF - Mustard G ($(ClCH_2CH_2)_2S$) - Phosphorous - Sulfur Dioxi (SO_2).

The health impact of several of these chemicals can be found in the RCR RFI Work plan. No particular location will be assumed for the phase II survey and a broad scan will be performed for all the chemicals at each o the surveyed areas. For most of the chemicals and in particular the chemicals that were used in the open environment, redistribution through the air and the surface and possibly the ground water make their present location (if still present in detectable quantities) difficult to predict. The survey should in particular find out if they have accumulated and where. The accumulation of a particular chemicals in a restricted area would be an ideal case and allow a more rapid and cost-effective remediation actio The fenced area that corresponds to the former location of the metal plating facility will be the only area for which a specific set of chemicals is expected: cyanides and metals. These chemicals are expected to have left traces in the upper part of the subsurface while their overall dissemination is a factor of the local hydrogeology.

c. Suitable Technology Considered

i. *Technology Considered: (5) Neutron Imaging*

(0) Abstract

The contribution of the neutron imaging technique specifically addresse the third goal of the project's statement of work: "in situ" chemical plum detection and mapping. The technique is based on the interaction c neutrons with the atomic elements of the soil. The technique allows t obtain information on the chemical composition of the near ground surfac without having to take samples. This technique also has the considerabl advantage that the analysis can be virtually performed onsite. Physicall as a result of the interactions of the neutrons with the soil element:

gamma-ray photons of specific energies are emitted. The energies of the gamma-rays are then used to detect the presence of the chemicals. The technique has been, in particular, successful for the detection of heavy metals such as lead or mercury and organic compounds containing chlorine such as trichloroethylene or PCB's. For the past 20 to 30 years, neutron imaging has been used for oil well logging and geological surveys. The use of the technology has been recently expanded to fields such as environmental surveys and food analysis. For environmental surveys, such as the one proposed here, the key technologies, including neutron sources, detectors, and data processing, are mature and commercially available. While all the elements of a probe are based on existing technology, the technique has yet to be applied extensively to the environmental field and the scope of the project will be to assemble and test a system to prove its efficiency for the MSFC site. In particular, computational and experimental simulations of the complex spectra acquired during this type of measurements will ensure a prompt and efficient analysis of the data during the onsite measurements. The tool will be assembled and tested at the Technology Development Laboratory of the Houston Advanced Research Center which has significant experience in developing such prototypes and has been working for several years with an oil company in developing chlorine tools for the down hole environment.

(1) Principles of neutron imaging

The principle of neutron imaging is illustrated in figure N1. A neutron imaging probe is composed of a neutron source, a high resolution gamma ray detector, an electronics and data processing package, and a cooling system for the detector. The neutron source emits neutron within the formation where they interact with individual atoms. The neutron-nucleus interaction results in the production of gamma ray photon(s) of specific energy(ies). The energy of the photon is determined by the particular nuclear reaction taking place. These reactions can be grouped in three different categories:

1. Inelastic gamma rays are emitted as neutrons collide with nuclides while slowing down in the formation.
2. Capture gamma rays are emitted when neutrons are absorbed by nuclides.
3. Activation gamma rays are emitted as nuclides release part or all the added energy acquired when they absorbed a neutron (delayed reaction).

While gamma rays emitted as a result of the first two processes are emitted almost immediately up to a few milliseconds, the third type of gamma rays are emitted with a delay depending upon their particular reaction. This distinction is important only if a pulsed system is used and the spectra are recorded at given time interval. At this point such technique does not seem to bring any significant additional advantages to the survey and will therefore not be further considered in this report. For

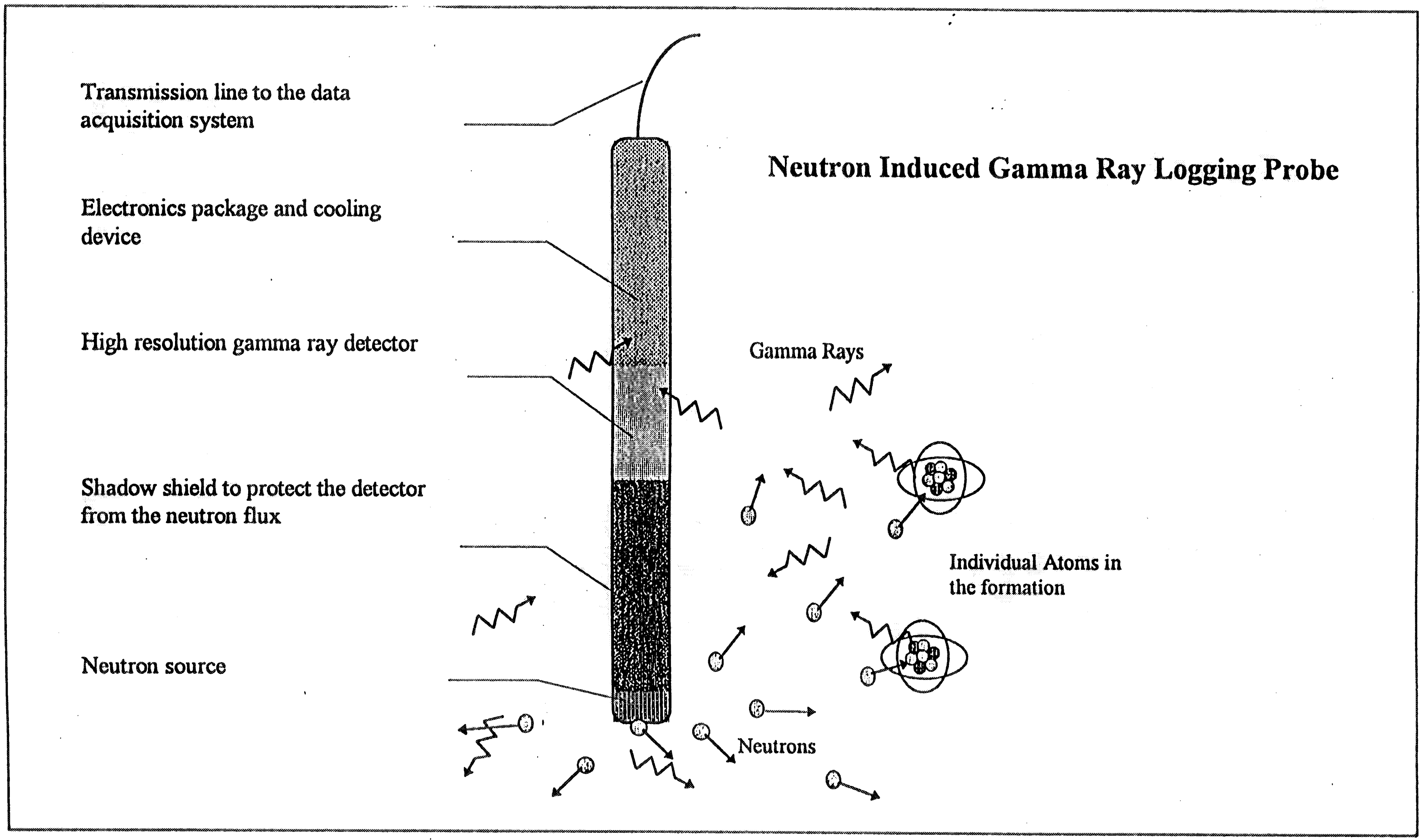

Figure N1. Schematic illustrating of the principle of the neutron induced gamma ray spectrometry technique also labeled neutron imaging. A neutron source emits neutrons into the surrounding formation - the neutrons interact with the nucleus of the atoms of the formation - characteristic gamma rays are emitted as a result of the nuclear reaction - a high resolution detector measures the energy of the gamma rays - from the resulting energy spectrum information is obtained as to the composition of the surrounding formation.

this survey, the spectra will be acquired while operating the neutron generator and for a period of time necessary to obtain good statistical data. The progression and dissemination of the neutrons across the formation including a simulation of the extend of the probed area will be presented in a later paragraph.

The second type of particles involved in the neutron imaging technique are the gamma ray photons generated during the nuclear reactions. They carry the information as to which elements are in the probed formation. But for this information to be recorded, the gamma ray detector must record the full energy of the photon. There are two factors that lead to the loss of the information. First, the detector itself must register as accurately as possible the total energy of the incident photon. A high efficiency, high resolution detector is therefore selected (large volume high purity germanium detector). The second cause for the loss of information is linked to the photons travel in the formation. While traveling through a material, photons undergo interactions which lead to the absorption of the photon or the loss of energy. If a photon loses part of its energy, the information as to the initial nuclear reaction and therefore the source element is lost. It is therefore only the uncollided photons that carry the information as to the composition of the surrounding formation. To register this information, the detector must be sufficiently close to the initial reactions to record enough uncollided photons. The uncollided photon mean free path is therefore an important factor for the survey set-up. Computations of the ranges of both neutrons and photons are presented in later sections.

To identify the presence of a particular element in the formation, one looks for the presence in the gamma ray spectrum of an energy line corresponding to a nuclear reaction involving the element. Figure N2 displays a gamma ray spectrum taken at HARC for a naturally radioactive soil sample. The sample has not been activated by neutrons but contains potassium, uranium, and thorium which are all naturally radioactive. Some of the energy lines are identified by indicating both the energy of the line and the source element. For an irradiated soil sample, there are a number of different elements and for each element there are often several nuclear reactions involved. The detector itself and the other structural elements of the probe can also contribute to the overall spectrum. Figure N3 (Ref. 1) illustrates an example of a spectrum showing both the influence of the detector housing and the formation. The raw spectra are relatively complex to analyze but the analysis can be somewhat streamlined if the elements of interest have been identified and if computational simulations and laboratory experiments have been previously performed. For the computational simulations, the code MCNP (Ref. 2) further described later in this section will be used to simulate energy spectra. Laboratory experiments will be performed to test the overall set-up, and to record the signature of the detector housing and the other structural elements of the probe. The tests will also involve experiments with soil samples from the beta site to verify that the energy lines selected to identify the presence of the chemicals of concern are

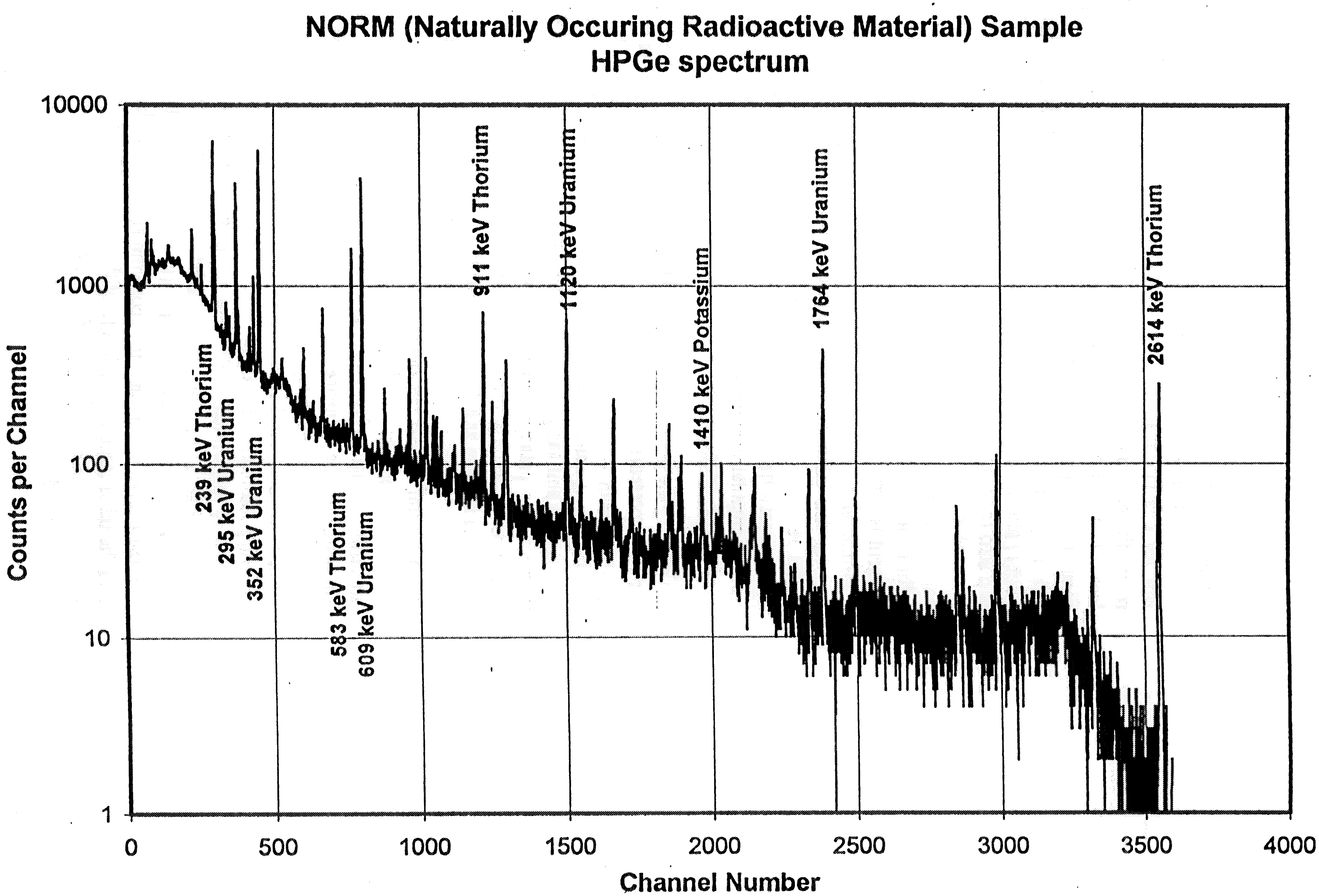

Figure N2. High Purity Germanium Spectrum of a soil sample containing naturally occuring radioactive materials (Uranium, Thorium, and Potassium). The different energy peaks are the result of specific nuclear reactions which allow for the identification of the ...

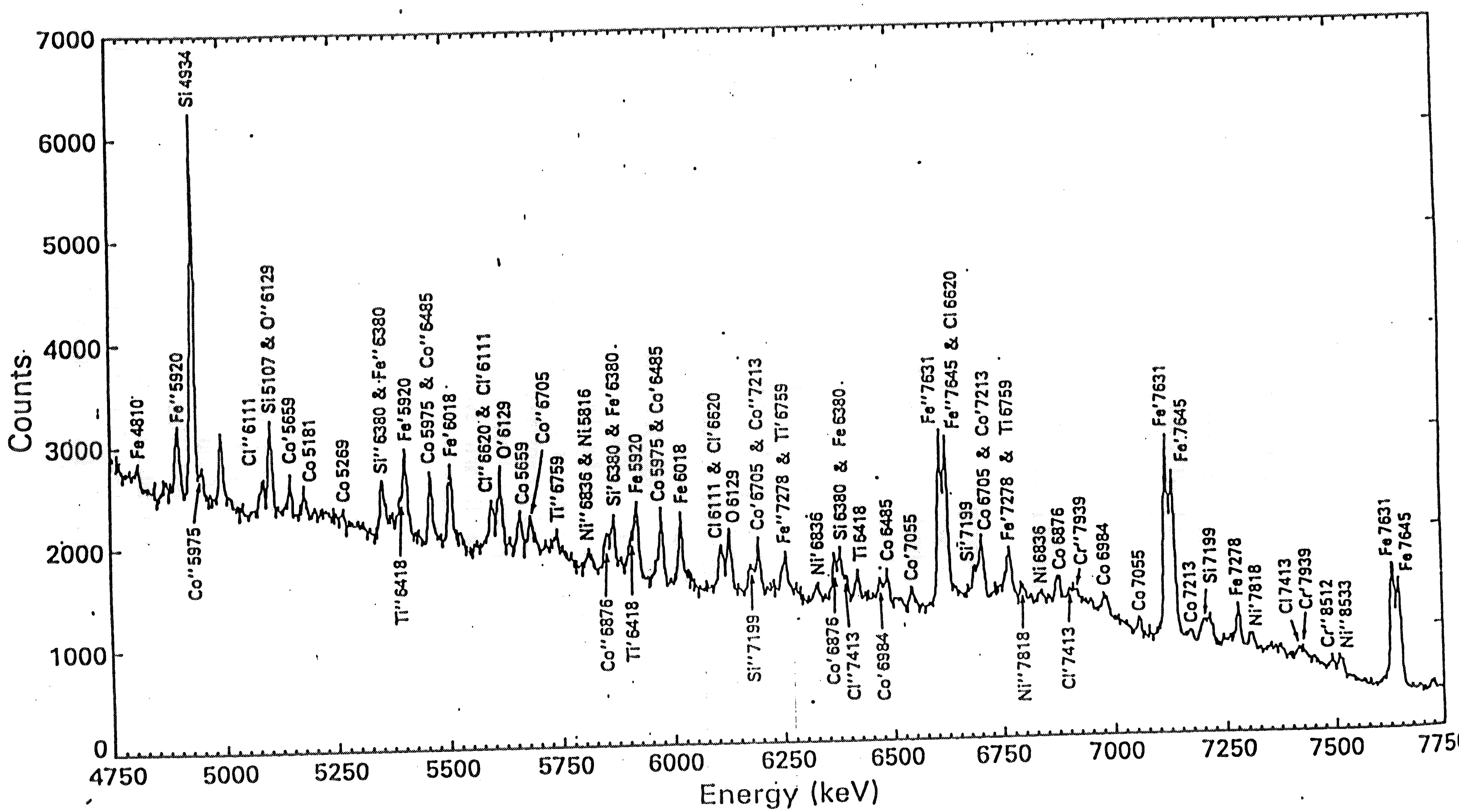

Figure N3. Capture gamma ray spectrum showing gamma rays from the detector housing in addition from the rock elements. Figure extracted from "Review of Nuclear Techniques in Subsurface Geology" by J.S. Schweitzer and D.V. Ellis in IEEE Transactions on Nuclear Science, Vol. 35, No. 1, 1988. The Ni, Co, & Cr peaks are from the cryostat while the Fe, Ti, & Si are from the rock formation.

indeed free of interferences from other elements of the soil or structural elements from the probe.

References:

1. J.S. Schweitzer & D.V., "Review of Nuclear Techniques in Subsurface Geology", IEEE Trans. Nucl. Sci., Vol. 35, No. 1, 1988.
2. R.A. Forster, R.C. Little, J.F. Briesmeister, & J.S. Hendricks, "MCNP Capabilities for Nuclear Well Logging Calculations", IEEE Trans. Nucl. Sci., Vol. 37, No. 3, 1990.

(2) Review of relevant neutron imaging techniques

Neutron imaging has been used in various forms since the early sixties for oil well logging (Ref. 1). The technique was not used to identify individual elements in the formations but allowed to acquire general information such as porosity by measuring the neutron transport properties of the formation. The use of a neutron source to irradiate the formation and a gamma ray detector to allow for the detection of individual elements in the formation started in the late seventies and early eighties in the petroleum industry (Ref. 2-4). The technique was also pioneered by institutions such as the US geological survey bureau to characterize rock formations and the quality of coal deposits (Ref. 6). More recently, the technique has been expanded to fields such as food analysis (Ref. 7) and biological sample analysis as well as environmental characterization (Ref. 8-9). For environmental surveys, the technology is mature as for the hardware used but is in its early stages as far as procedures and previous work. However, since the basics of the technology are the same as for the more mature applications, the adaptive steps are not seen as a major problem and the technology promises to be successful and have a significant impact on environmental surveys in the immediate future.

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3. J.A. Grau & J.S. Schweitzer, "Elemental Concentrations from Thermal Neutron Capture Gamma-Ray Spectra in Geological Formations", Nucl. Geophys., Vol. 3, No. 1, 1989.
4. J.S. Schweitzer, C.A. Peterson, & J.K. Draxler, "Elemental Logging with a Germanium Spectrometer in the Continental Deep Drilling Project", IEEE Trans. Nucl. Sci., Vol. 40, No. 4, 1993.

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7. D.L. Anderson, W.C. Cunningham, & G.H. Alvarez, "Multielement Analysis of Foods by Neutron Capture Prompt Gamma-Ray Activation Analysis", J. Radioanal. & Nucl. Chem., Vol. 167, No. 1, 1993.
8. J.H. Chao & C. Chung, "In Situ Lake Pollutant Survey Using Prompt-Gamma Probe", Appl. Radiat. Isot. Vol. 42, No. 8, 1991.
9. J.H. Chao & C. Chung, "In Situ Prompt Gamma-ray Measurement of River Water Salinity in Northern Taiwan using HPGe-^{252}Cf Probe", Appl. Radiat. Isot. Vol. 42, No. 8, 1991.

(3) Suitable interactions for each of the identified chemicals

As detailed in a previous section, each element in the formation can be identified by a particular nuclear reaction taking place between an incident neutron and the nucleus of the element. Each nuclear reaction results in the release of gamma ray(s) of particular energy(ies). The selection of a particular energy line is based on potential interferences from other elements and based on the relative probability of gamma ray emission (related to the reaction cross section). An ideal line has no potential interfering lines and generates a strong signal for a given elemental concentration in the formation. The chemicals identified in an earlier section were grouped by element and a specific energy line was identified for each of these elements. The energy lines were selected from lines previously used and reported in the litterature and for which no interferences were recorded. These lines will also be tested experimentally with the completed probe. Other lines could be selected if an unforeseen interference was to complicate the measurements.

Types of Chemical	Gamma Ray Line	Chemicals of Concern
Metals		
Aluminum (Al)	1.78 MeV[1,2]	Aluminum
Cadmium (Cd)	0.59 MeV[2]	Cadmium
Chromium (Cr)	8.88 MeV[1]	Chromium
Copper (Cu)	1.04 MeV[2]	Copper
Lead (Pb)	7.37 MeV[2]	Lead
Nickel (Ni)	9.00 MeV[1,2]	Nickel
Silver (Ag)	0.66 MeV[2]	Silver
Zinc (Zn)	7.86 MeV[2]	Zinc
Other elements		

Boron (B)	0.48 MeV[1,4]	Boron oxides
Chlorine (Cl)	6.6 MeV[2,3]	TCE ($CHClCCl_2$) - Chloroform ($CHCl_3$) - Perchloroethylene ($(CCl_2)_2$) - DDT ($(ClC_6H_4)_2CH(CCl_3)$) - HCl - Mustard Gas ($(ClCH_2CH_2)_2S$)
Fluorine (F)	to be determined	Hydrofluoric acid (HF)
Nitrogen (N)	5.27 MeV[2]	Cyanide (CN^-)
Phosphorous (P)	to be determined	Phosphorous
Sulfur (S)	2.38 MeV[2]	SO_2

As can be seen in the table, the analysis for the metals will be simple a the elements will be detected directly. For the other elements and chlorin in particular, the detected element will potentially be related to sever chemicals. A different type of analysis would have to be performed t confirm the exact nature of the chemical. This is however not a majo drawback as the major goal of the survey is to locate and map areas wher the presence of some of the elements is recorded. The exact determinatic of the nature of the chlorine based chemical can be left for a more detaile and localized survey.

The following chemicals were not included in the list: Benzo(a)pyren ($C_{20}H_{12}$) - Benzene (C_6H_6) - Xylene ($(CH_3)_2C_6H_4$). Their atomi composition is based on materials that are also found in the soil an therefore only unusually large quantities would be detected. Thes chemicals have all the particularity of being light volatile organi compound. If the penetrometer technology is selected, it would relativel simple to integrate a detection system targeted towards light volatil chemicals such pyrolysis or a combination of a sniffer and a small mas spectrometer. Beryllium was not included either in the list and wi probably not be detected by this technique.

References:

1. J.L. Mikesell, F.E. Senftle, R.N. Anderson, & M Greenberg "Elemental Concentrations in Diabase Determined by High Resolution Borehole Gamma-ray Spectrometry", Nucl. Geophys. Vol 3, No. 4, 1989.
2. F.E. Senftle & J.L. Mikesell "The nuclear ratio technique applied to borehole exploration for industrial metals and coal", Nucl. Geophys. Vol.1, No. 3, 1987.
3. J.H. Chao & C. Chung, "In Situ Lake Pollutant Survey Usin Prompt-Gamma Probe", Appl. Radiat. Isot. Vol. 42, No. 8, 1991.
4. J.S. Schweitzer, R.C. Hertzog, & P.D. Soran, "Nuclear Data fo Geophysical Spectroscopic Logging", Nucl. Geophys., Vol.1, No. 3 1987.

(4) Choice of the neutron source(s)

Two general types of neutron sources are readily available for neutron imaging: chemical sources and accelerator based sources. Chemical sources are usually based on a mixture of an α-emitter such as Americium or Plutonium and Beryllium: AmBe and PuBe. These sources emit neutrons within a broad energy spectrum up to about 12 MeV with the largest fraction of the neutrons emitted between 2 and 6 MeV. The accelerator tubes accelerate deuterium ions into a target containing deuterium (D-D source) or Tritium (D-T source). The D-D sources produce 2.45 MeV neutrons while the D-T sources produce 14.1 MeV neutrons. The energy of the neutrons will mainly affect two parameters: the type of inelastic interaction taking and the range of the neutrons in the formation. The first parameter is not critical for this survey since inelastic scattering will not be one of the major interaction modes used. The second parameter is neutron mean free path into the formation and is of significant importance for the surface measurements. The larger the area covered by the emitted neutrons, the larger the area sampled at one time as the gamma ray detector can be moved around while keeping the neutron source and the electronics in place. Accelerator sources also have the significant advantage to emit neutrons only when activated and are therefore easier to transport and handle. A 14.1 D-T accelerator source is therefore the selected source for this project.

(5) Initial calibration and testing protocol

To conduct the survey, a modular probe which allows a quick conversion from a surface measurement to a well measurement configuration will be assembled. The probe itself will have to be tested including the neutron source, the gamma-ray detector, and the electronics and data acquisition package. This testing can be done in the laboratory and initial tests with soil sample taken on the MSFC site will also be performed. Also, before taking measurements in the field, it is highly desirable to test the tool in a test hole. These facilities have a series of well calibrated formation surrounding a borehole. Such testing will not only allow to test the equipment and the procedures but will also give the opportunity to analyze and compare the results for a series of known formations. Another results that must be obtained from the testing of the tool are a typical spectra resulting from the interaction of the neutrons and the tool structure.

ii. *Limitations of Neutron Imaging*

(1) Investigative range of the technique

The range of the neutron imaging technique can be seen as both a considerable advantage if compared to the usual chemical analysis techniques or as a limitation if compared to the range of seismic or EM type measurements. The neutron range varies between a couple of feet for hydrogen rich content soils to up to 10 to 12 feet for dry terrains. The photon ranges are in general around a couple of feet and increase when there is no high Z materials in the formation. The ranges of photons and neutrons in the modelized MSFC soil were simulated by using the Monte Carlo Code MCNP developped at Los Alamos National Laboratory (Ref. 1). For both cases a spherical geometry was set. The neutrons or photons are emitted from a point source in the middle of a series of spherical shells. The neutron or photon populations are recorded for each shell which gives a measure of the total volume irradiated. The scalar fluxes at the boundaries between each spherical shells are also displayed.

(a) Neutron ranges in the beta test soil

The result of the MCNP simulations for neutron ranges in the beta test soil for 14 MeV neutrons are displayed in figure N4. The measurement range to be selected for the measurements results from a trade off between the neutron flux and the measurement time. From figure N4, a neutron range up to 80 to 90 cm can be used as a reference for initial estimates. For longer counting times, the neutron flux could be sufficient at distances up to 200 to 250 cm. For surface surveys, it might become more cost efficient to move the neutron source more often and reduce the counting time by not trying to extend to much the distance between source and detector. For the phase III large scale survey, the source and detector will probably be mounted on a vehicle and the source and detector will be relatively close to each other. The larger area will then be covered more cost efficiently because of the ease of movement of the probe.

(b) Gamma-rays ranges in beta test soil

Because it is the uncollided photons originating from a particular nuclear reaction that allows for the identification of a specific chemical, the range of the photons is important for the evaluation of the range of the technique. The result of the MCNP simulations of photon ranges in the beta test soil for 6.6 MeV photons (chlorine) are displayed in figure N5. The 6.6 MeV chlorine line was chosen because of its importance for the the detection of several of the chemicals of concern. The measurement range then becomes the sum of the neutron range and the photon range, about 40 to 60 cm. The detector can therefore be moved up to about 120 to 150 cm from the source. These are first order estimates and will be refined during the phase II study. These ranges also depend on the water content of the soil and its exact composition. These ranges can also be somewhat extended for specific applications where the range is at a premium by extending the counting time and/or using a higher intensity source.

(2) Elemental characterization

As detailed in the section describing the fundamentals of the technique, the neutron imaging technique allows the detection of individual elements. This can be seen as an advantage and is listed in the attributes of neutron imaging. This is also a limitation for chemicals that contain only elements that are already part of the soil composition of for a series of chemicals

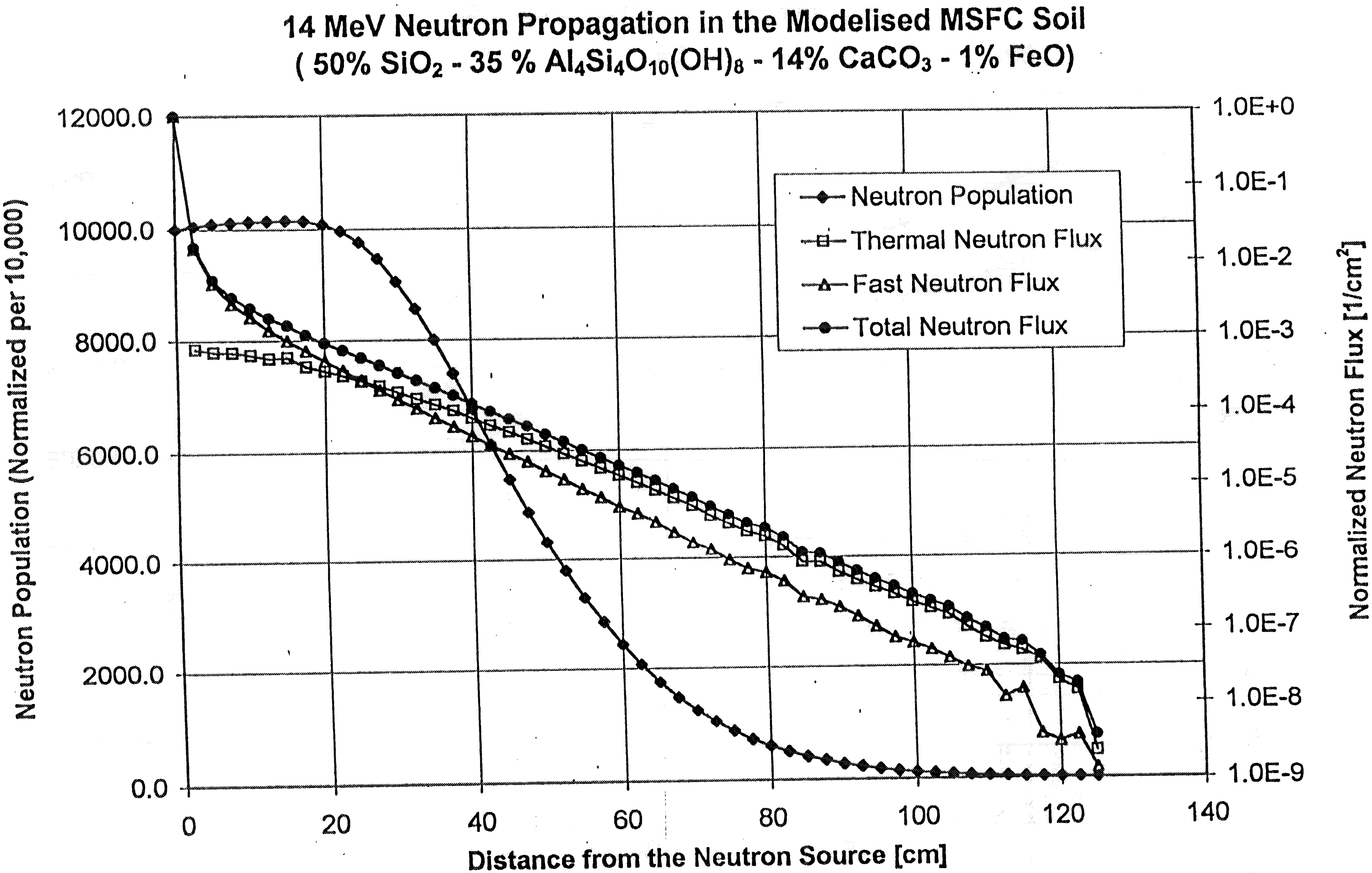

Figure N4. MCNP4a simulation of the propagation of 14 MeV neutrons in a modelized soil similar to the one found on the MSFC beta site. The problem was set as a poiint source surrounded by spherical shells. The neutron population is the population in each shell and the flux is the scalar flux at the boundary between each spherical shells.

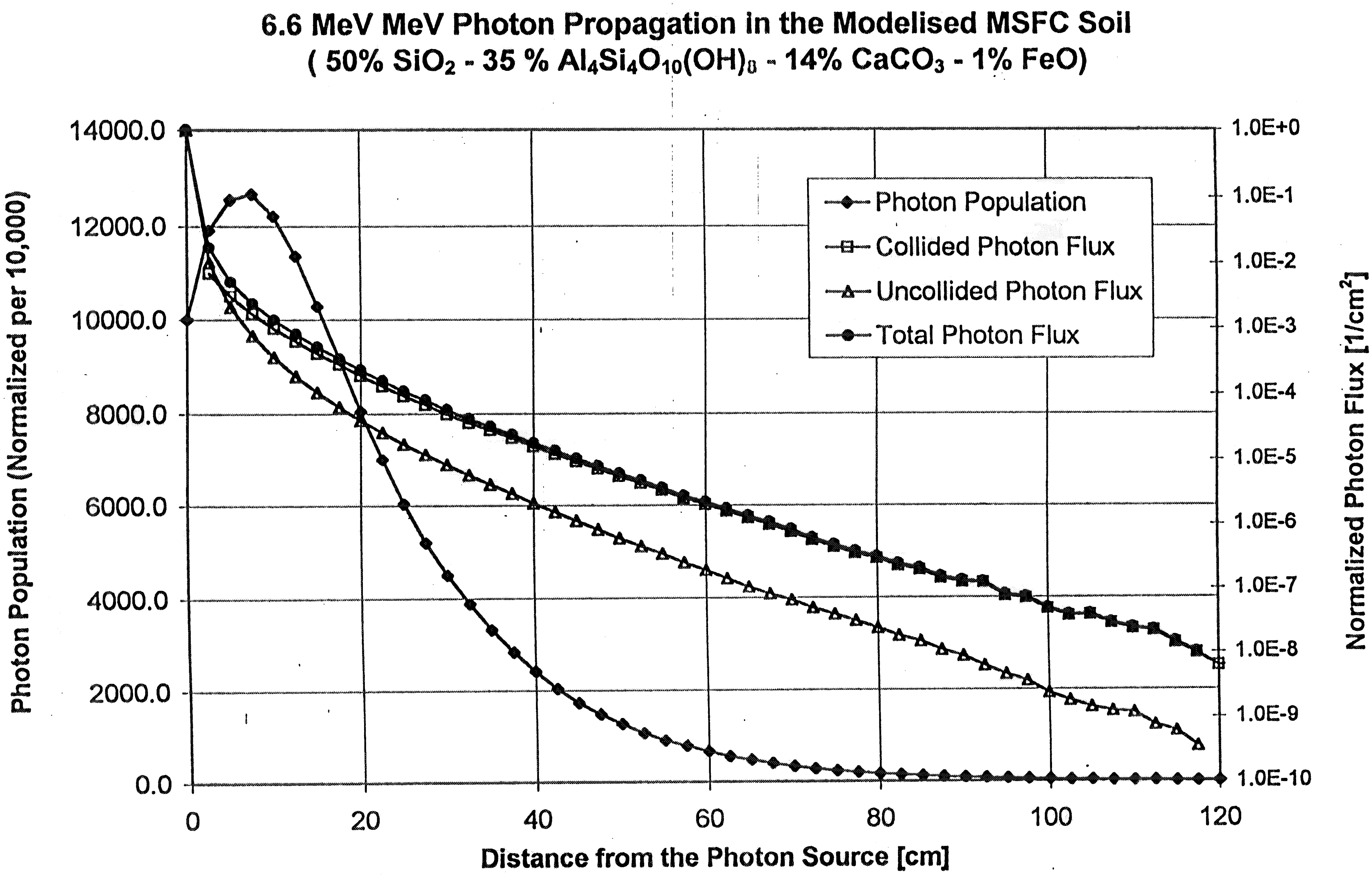

Figure N5. MCNP4a simulation of the propagation of 6.6 MeV photons in a modelized soil similar to the one found on the MSFC beta site. The problem was set as a poiint source surrounded by spherical shells. The photon population is the that share the same elemental composition. In the case of a chemical composed of elements present in the soil matrix, the chemicals can be detected only if an additional impurity is part of the chemical composition. For the case of chemicals sharing the same elemental composition such as chlorine based organic chemicals for this study, other characterization techniques must be used in conjunction with the neutron imaging unless different impurities can be found to be part of the chemicals. It is worth mentioning that even if the neutron imaging technique does not distinguish between chemicals of same elemental composition, the technique still indicates that presence of their common element. The complementary chemical characterization technique can then be used for only the identified area.

References:
1. R.A. Forster, R.C. Little, J.F. Briesmeister, & J.S. Hendricks, "MCNP Capabilities for Nuclear Well Logging Calculations", IEEE Trans. Nucl. Sci., Vol. 37, No. 3, 1990.

iii. *Attributes of Neutron Imaging*

(1) Elemental characterization

A significant advantage of this technique is that most of the elemental compounds of a soil including the potential pollutants, can be detected individually and insitu by the same technique. Most of the other chemical characterization techniques identify the presence of a particular element only indirectly and several different techniques must be used to perform a broad scan survey. Also, sophisticated chemical characterizations must usually be performed in the laboratory environment, requiring extraction and transport of the soil samples.

(2) In Situ Measurements

As mentioned previously, for most chemical characterization techniques, a survey is conducted in two steps: samples are extracted in the field and then transported to a laboratory for experiments. For the neutron imaging technique, an automated data acquisition system can be set to identify the presence of the energy lines corresponding to the chemicals of concern. The presence of a chemical in the soil can therefore be immediately detected and additional more sensitive measurements performed. The flexibility of insitu measurements and analysis are one of the more significant advantages of the technique.

(3) High sensitivity

The sensitivity of the neutron imaging technique will vary for each element. The sensitivity depends in particular on the probability that a neutron will interact with the particular element (reaction cross section) and the probability that the gamma ray of interest will be emitted during or following the interactions. Minimum detection concentration in the parts per million are to be expected. For elements for which experiments were conducted yielded the following minimun detectable concentrations (Ref. 1): Chlorine (1.16 MeV line) 86 ppm - Mercury (0.368 keV line) 33 ppm - Cadmium (0.559 MeV line) 1.4 ppm.

References:
1. J. Burnham, J. Conaway, J. Duray, S. Frankle, D. George, J.L. Mikesell, P. Nelson, R. Wilson, "Contaminants Detection Thresholds for the Multispectral Neutron Borehole Logging Method: Preliminary Report", DOE Report DOE/ID/12584-188 GJPO-TP-6.

(4) Volumetric averaging

For a drill and sample technique, only the drilled core is available for analysis. The volume sampled is therefore relatively limited. As simulated in the previous section, a volume of about four cubic feet is sampled for the MSFC type terrain. Also, there is a strong possibility with the drilling and sampling technique for contamination of the sample. For insitu neutron imaging, the measurement is made on site without extraction and transport of the sample. If a casing is involved or if the measurements are made in a well with a particular structure, the interference from the structure can be measured or simulated computationally and taken into account in the analysis.

(5) Through-casing measurements

One of the attractive features of the neutron imaging technique is its ability to be performed through structures such as the casing of a well or the metal wall of a penetrometer. The neutrons and gamma rays penetrate steel and other metals, the technique can therefore be applied without direct physical contact with the formation. Existing wells, for example, can be used without any further modifications provided that their diameter is sufficient for the tool (> 3"1/2). The structural composition of the well or penetrometer will influence the overall recorded spectra by somewhat reducing the formation volume sampled (now partly occupied by the well or penetrometer structure) and by adding energy lines corresponding to the structural materials. These lines however should not interfere significantly with the lines selected to measure the presence of the chemicals of concern.

d. Logistics of Operations

i. *Platform*

(1) Non invasive measurements (surface)

For this type of measurements, only the near ground surface (about 2 ft.) is sampled. For most of the pollutants that penetrate into the ground, sufficient traces should be left in the upper ground surface to be detected

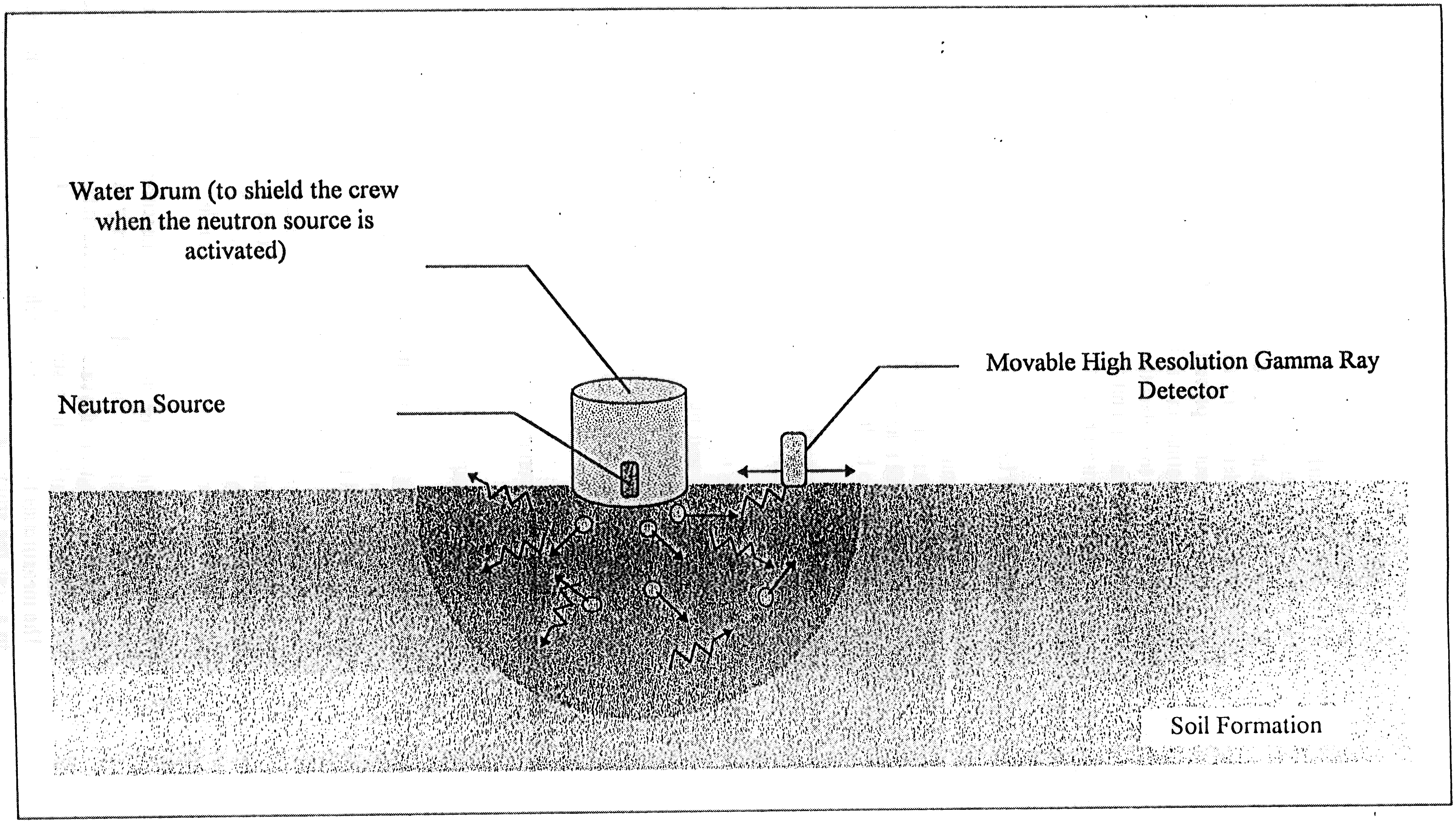

Figure N5. Schematic illustrating the deployment of a neutron induced gamma ray probe as devised for the survey of the MSFC beta site - Deployment for surface measurements. A neutron source emits neutrons into the soil, the neutrons interact with individual atoms in the formation and Gamma rays are emitted. A high resolution gamma ray detector is moved around the irradiated area and spectra are recorded. A truck is required to transport the equipment and a vehicle must also be used to move the large water drum used to shield the neutron source.

by the neutron imaging technique. Also, if the pollutants are periodica! brought to the surface by rising ground waters, detectable traces could left in the near surface. This would be in particular useful for isolat underground pools that keep significant concentrations of pollutar trapped. If such features could be identified, the remediation action wou considerably simpler and more efficient. A schematic of the set-up for t surface measurements is presented in figure N5. The source is placed at predetermined location and a hollow drum filled with water is plac around the source to protect the crew. The gamma ray detector is mov at different locations around the source. The neutron source is activat only during the measurements. A spectra is collected for each of t locations.

The technique will be tested in the following areas of the beta site:

1. The area around well 28d.
2. The fenced area of the formeer metal plating facility.
3. Along the small road crossing the wooded area of the beta site.
4. In two areas to be determined where the pollutants presence is thoug to be minimal.
5. In other areas to be determined to correlate the measurements wi other techniques.

The success of the technique will be determined by its ability to measu surface pollutants and by its ability to predict, from the near surfac traces, the presence of chemicals deeper in the soil. If the technique successfull, a vehicle containing the source and the detectors could t designed for phase III and a continuous measurement type survey could t conducted.

(2) Semi-invasive measurements (cone penetrometer)

The surface technique is limited by its investigative depth of about 2 fee For this reason, the neutron imaging technique is mostly used in th context of well logging. The neutron imaging technique will be tested i the compatible existing wells (well 28d of the beta site). However th number of available wells is limited and setting up sampling wells for large area would be relatively expansive. It is proposed here to use technique called cone penetrometer in which a large metallic cone followe by a hollow casing is ramed into the gorund. The cone penetromete technique is much faster than settint up wells. Yields of up to 12 to 1 cone penetrometers per day should be achievable.

The survey geometry for the well type measurements is illustrated i figure N6. The probe is lowered progressively into the well and spectr are acquired at regular intervals. The measurements will provide a pictur of the underground volume surrounding the well or cone penetrometei The measurements will also be correlated with the surface measurement to assess the ability of the surface measurements to predict the pollutan

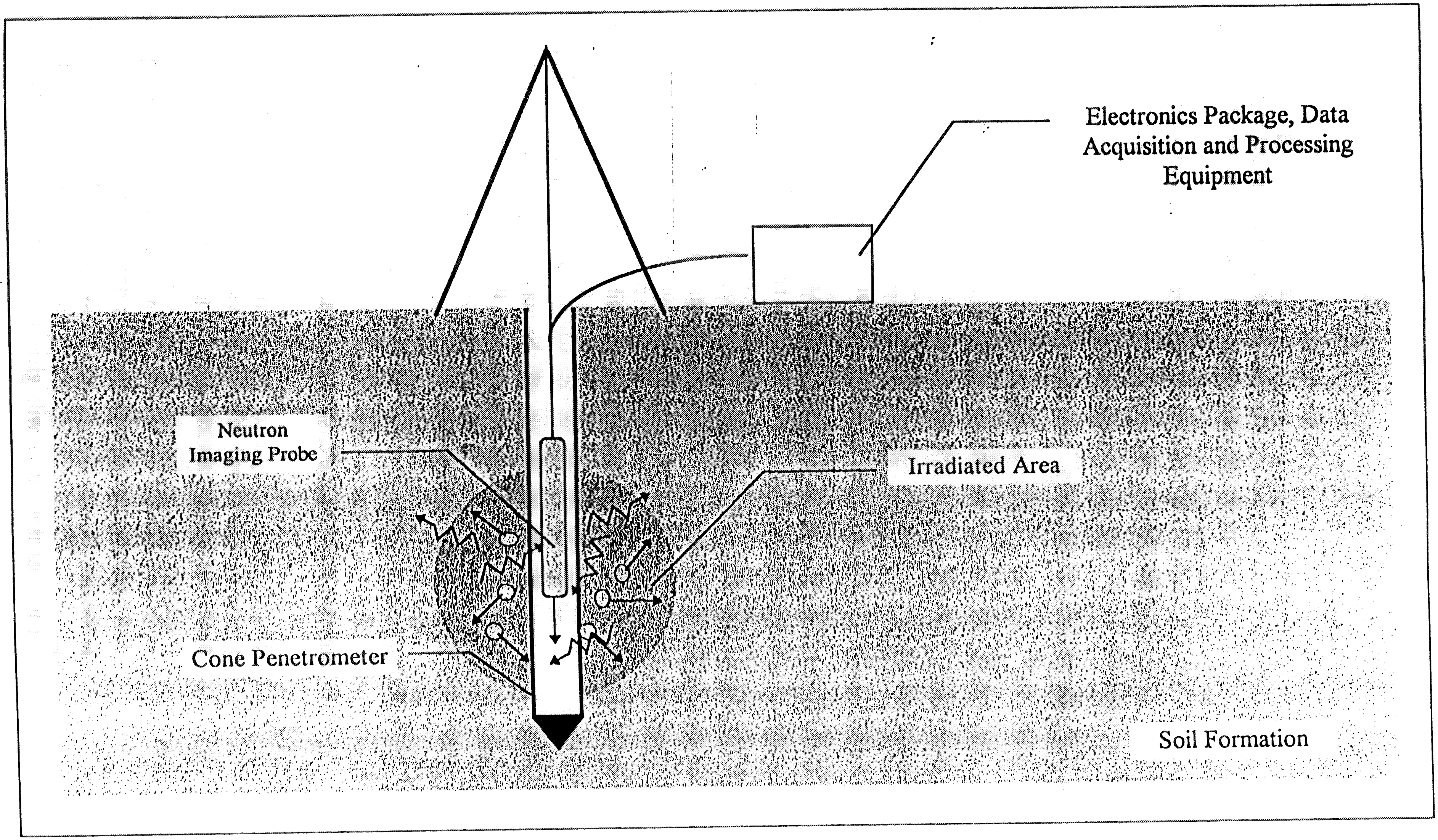

Figure N6. Schematic illustrating the deployment of a neutron induced gamma ray probe as devised for the survey of the MSFC beta site - Deployment for wells and cone penetrometer. The probe is progressively lowered in the well or penetrometer. At repeated intervals, the probe is stopped and a measurement is taken. The neutrons are sent across the casing into the formation where they interact with individual atoms. The resulting gamma rays returning towards the probe are recorded by a high resolution gamma ray detector. Information about the elemental nature of the soil is extracted from the spectra.

content of deeper levels of the soil. Besides well 28d, 4 other areas were selected for well type measurements.

1. In the fenced area of the formeer metal plating facility.
2. Along the small road crossing the wooded area of the beta site.
3. In two areas to be determined where the pollutants presence is thought to be minimal.
4. Possibly in other areas to correlate measurements with other techniques.

ii. *Surface Condition Factors*

For the neutron imaging survey, the surface conditions will have an influence on two different aspects of the measurements. First, the water content of the near ground surface somewhat influences the neutrons range. The higher the water content, the smaller the neutron range. This affects mainly the surface measurements where the detector is moved away from the source and the range of the measurements depend on the extend of the irradiated surface. It is recommended to perform the survey during the fall, probably in October, when the precipitations are low and the ground has been dried during the summer. The other aspect of the measurements affected by the surface conditions is the vehicle mobility. For the surface measurements, moving the large water drum used for the radiation shielding will be difficult with a rudimentary set-up. Also, the electronics equipment and the generator will be located on a trailer. In the case of measurements made with a cone penetrometer, a heavy vehicle must be used and therefore the accessibility of the site is again a factor. For the beta site, the area affected by the surface condition is mainly the wooded swamp area in the southwest part of the site. For the phase II surveys, the measurements will be made only on the road crossing this area. For the phase III measurements, the possibility to survey these areas will depend on the procedures, equipment, and vehicles chosen for the final full scale deployment.

iii. *Cost Estimates*

(1) Parameters affecting the cost of the measurements

The phase II survey is well established and the equipment and survey procedures have been selected to minimize capital expenditures. The application of the neutron induced gamma ray spectroscopy (neutron imaging) to an environmental survey is nevertheless relatively new and some expenditures are related to adaptation of the existing equipment. The budget for the phase II effort is detailed below. The exact survey procedure for phase III will somewhat depend on the results obtained in phase II. The estimates presented here are based on the assumption that surface measurements will give an indication as to the presence of chemicals located deeper into the soil. The survey will then be conducted in three phases:

1. Surface survey with a moving vehicle for a coarse mapping of the identified chemicals in the near surface.
2. Measurements using a cone penetrometer on a wide grid to complement the surface mapping. This additional step might be necessary only in particular areas depending on the phase I results . A mesh size of about 300 ft. is used for this estimate.
3. Additional measurements using the cone penetrometer at the hot spots detected with the surface mapping.

The mesh size selected for the cone penetrometer type survey will be an important factor. The use of the cone penetrometer itself increases significantly the rate at which boreholes are set-up as compared to a regular drilling and casing procedure. The cost analysis for phase III is presented a the end of this section.

(2) Cost estimates for the development and application of an experimental system (Phase II)

For the phase II of the project, only a relatively small area will be surveyed, and therefore, a smaller scale and less flexible system can be set-up for proof of concept measurements. A large fraction of the equipment used will come from HARC or will be borrowed or leased from other institutions collaborating with HARC. The high purity germanium detector will be provided by HARC, the neutron source (14 MeV D-T accelerator tube) will be provided through a licensed subcontractor who will also be one of the main consultants for the project and participate in the testing. No additional facility use for HARC besides the regular overhead in the salaries was added to the budget. The total proposed budget is detailed hereafter:

Scientist	$ 56,401
Environmental Consultant	$ 11,970
Supporting scientist	$ 6,944
Machinists & Technicians	$ 31,500
Cost for use of WRT Equipment	$ 10,500
Cost for use of CEBAF Facility & Equipment	$ 10,500
Licensing fees & Procedures	$ 5,000
Shallow hole probe dewar	$ 3,500
Hydraulic system for large movable water drum	$ 3,150

Trailer, power generator, & trailer set-up	$ 8,40(
Electronics equipment for probe operation, Notebook computer and programmable software for peak identification	$ 15,75(
Trips for scientist, technicians, and consultants (9 trips)	$ 18,90(
Nominal fee	$ 7,485
Total	**$ 190,000**

(3) Cost estimates for a large scale or commercial system (Phase III)

The cost of a commercial system can be divided in three different parts: Hardware costs - Development and testing costs - Operational costs. The methodology used to obtained the estimated operational costs is first described, and the cost estimate is then presented.

Surface operation:

The surface survey consists of a vehicle slowly scanning the area of interest. The cost of the surface operation is dictated by the mesh size adopted to scan the area and by the scanning speed. If a 20 ft. grid is selected a 4,356 ft. trace is required to cover an area of 1 acre. In this case, the detector will be located as close a possible to the neutron source while maintaining a sufficient shield thickness to protect the integrity of the detector. The detector count rate will not be a limitation in this set-up because of the high count rates near the source. The limitation to the surface mapping rate will therefore be the speed at which the relatively logging vehicle can operate. Assuming a logging speed of 2 mph or 10,560 ft/hr, adding about 30% of the distance for maneuvering leading to an effective logging speed of 8,123 ft/hr, 1.86 acres could be covered per hour. If two hours a day are discounted for refueling, transport to the measurements site and preparation of the area to be mapped, a total daily trace of 48,738 ft could be achieved. This correspond to a total area of about 11 acres per day. Assuming that the capital expenditures are already taken into account, the main cost will be the logging crew composed of a scientist or engineer, a technician, and miscellaneous operating costs such as fuel for an estimated total of $ 150/hour. The survey cost would therefore be about 110 $/acre. The cost depends heavily on the choice of the grid size and the logging speed. The logging speed is directly dependent on the terrain conditions. Wooded areas, for example could not be covered by this technique, and a portable equipment would have to be set up for this type of terrain. The results of the phase II survey will be necessary to refine the strategy and the cost-estimate of the technique.

Cone penetrometer operation:

For the cone penetrometer application, a service company will be hired at a rate of about $ 1,000 per day. A total of 8 to 15 cone penetrometers can be set-up in one day depending on the terrain conditions. Using 10 cone penetrometers as a daily reference a price of $ 100/cone is assessed. the logging of a cone penetrometer will depend on the depth of the penetrometer and the number of spectra. Assuming an average depth of penetration of 30 ft. and a spectrum every 5 ft., an acquisition time of 10 minutes per spectrum, the average logging time for a penetrometer will be 1 hour. To include time for transport and set-up of the equipment, a total of 1 hour and 40 minutes will be assessed per cone. The daily rate for the logging would therefore be about 5 boreholes per day. Assuming that capital investments have already been accounted for, the logging price will be mainly be the cost of the logging crew which will be typically composed of a scientist or engineer and 1 or 2 technicians and . A cost of $ 1,200/ day is attributed to the logging operation. If a mesh size of 300 ft. is selected, 1 cone penetrometer will be installed for every 2 acres area. The total cost per acre is therefore $ 50 (cone installation) + $ 120 (logging) = $ 170 / acre. It is emphasized that the grid size has a very large influence on the cost and that depending on the results obtained for the surface measurements as well as other techniques, the grid size could be adjusted or the technique used only at particular hot spots.

Hardware costs - borehole probe:

Logging truck with logging hardware (not fully equipped)	$ 50,000
High efficiency HPGe detector (efficiency > 30%)	$20,000
Shallow hole cryostat (liquid nitrogen dewar)	$ 3,500
14 MeV D-T source	$ 50,000
Detective Portable Gamma-Spectroscopy system	$ 14,000
Electronic equipment including cables-interfaces Notebook computer and software allowing programmable automatic peak identification	$ 25,000
Total	**$ 162,500**

Hardware costs - Surface probe:

Custom truck with shielding	$ 50,000
High efficiency HPGe detector (efficiency > 30%)	$20,000

Large Cryostat (liquid nitrogen dewar)	$ 3,50(
14 MeV D-T source	$ 50,00(
Detective Portable Gamma-Spectroscopy system	$ 14,00(
Electronic equipment including cables-interfaces Notebook computer and software allowing programmable automatic peak identification	$ 25,00(
Total	$ 162,50(

Development and testing costs:

Development of a specific Penetrometer with diameter > 3" 1/2	$ 60,00(
Development and Packaging of the two probes	$ 300,00(
Testing of the probes	$ 300,00(
Total	$ 660,00(

Operational costs:

Semi-invasive method (coarse mesh)	$ 170 / acre
Surface survey (fine mesh)	$ 110 /acre

e. Data Collection & Analysis

i. *Data Collected/Results*

For each test location, the results will consist of gamma-ray energy spectra similar to the one presented in figures N2 and N3. For well 28d and for the areas in which cone penetrometers have been used, the data will also consist of several spectra corresponding to different depths. For the surface measurements, the spectra will be collected at different locations around the neutron source. The actual chemical detection will be completely based on the energy spectra which will be analyzed based on site specific simulations, the available literature, and previous experience.

ii. *Analysis*

(2) Chemical characterization

For each test location, the analysis will consist of assessing for the presence of the pre-identified chemicals by analyzing the gamma ray spectra. If the characteristic signature of a chemical is found in the spectrum, the intensity of the particular line will be recorded for that location. It is important to remember, as explained previously, that neutron imaging detects the presence of elements composing a chemical and not the chemical themselves. For example, DDT, TCE, and PCB's all contain chlorine. The neutron imaging technique will detect for the presence of chlorine but would have to detect for other elements composing these chemicals to trace back the exact composition of the pollutant. This will not be a problem for metals since they are already elements. For other chemicals, such as organic compounds, a true chemical characterization can be achieved only if enough of its components can be detected. However, the purpose of the neutron imaging technique is foremost the detection and mapping of hot zones. Once the location of the hot zones has been determined, other techniques involving sampling can be applied with the knowledge of at least one of the elements of the chemical. Also, the cone penetrometers could be used to house other techniques addressing more specifically the detection of volatile organic chemicals or other chemicals of primary concerns.

(3) Modeling of potential plumes

For the surface-type measurement, a "plume modeling" will be completed for each element detected in the test area. The modeling will be completed by mapping the signal intensity of the element of concern over the tested area. The technique will be in particular emphasized to map for the presence of chlorine and heavy metals. This mapping will be contingent upon the successful application of the surface detection method. If the cone penetrometer method is used, a mapping of the underground will also be possible over the area investigated with the penetrometers.

iii. Data Packaging

For the neutron imaging technique, the final data will be a list of the identified elements of concern with their signal intensity at each test locations. The available data will also include, for reference, the gamma ray spectra obtained at each location with the measurement parameters. For the areas in which a particular chemical was detected in the near surface, surface maps indicating for the presence of the chemical will drawn.

f. Conclusions & Recommendations

The neutron imaging testing is recommended for the mapping of the presence of chlorine and heavy metals and possibly other elements such as nitrogen at the surface and near surface of the Marshall Space Flight Center. The mapping of these elements should allow to locate more precisely the sources of the different pollutants and allow to set-up a more specific and less expensive remediation program. The recommended system hardware to conduct this survey is a probe consisting of a high resolution gamma ray detector (High efficiency High Purity Germanium detector), a small Deuterium-Tritium Accelerator tube providing a 14

MeV neutron source for maximum penetration in the formation, broadest excitation potential for inelastic gamma rays, and ease of manipulation while not in operation, and a portable fast and user friendly electronics and data acquisition system to allow for quick in-situ analysis of the data and portability during surface measurements. The deployment of the technique is recommended for well 28d, the only well on the beta site to have a sufficient diameter to use a neutron imaging tool, for the selected surface areas as well as for a selective use of cone penetrometers for the targeted areas.